AN INTRODUCTION TO TROPICAL SOILS

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AN INTRODUCTION TO TROPICAL SOILS

BY

DR. P. VAGELER

TRANSLATED BY

DR. H. GREENE

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I have to thank also my colleague, Mr. O. W. Snow, for correcting proofs, and my wife for help in preparation of the Index.

H. GREENE

GEZIRA RESEARCH FARM, WAD MEDANI,
SUDAN, *November* 1932

FOREWORD

Dr. Paul Vageler needs no introduction to students of tropical agriculture. He has spent some twenty years in the tropics: before the War as agricultural expert to the German Government at Dar-es-Salaam, afterwards as agricultural chemist at the Dutch Tea Research Station in Java. He then travelled extensively to study soil problems, first exploring Persia; then the Lake Victoria district in East Africa, where he examined, among other things, the possibilities of irrigation; more recently he visited the Sudan, making detailed studies of the soils and agricultural conditions of the Upper Nile and the Gash—regions of great importance to the cotton industry.

In this book he summarises his impressions and his experiences with tropical soils. It is not a text-book in the ordinary sense, and it makes no pretence of being an index to the extensive literature now grown up around the subject. It is, however, for that very reason easier to follow, and it does convey a good impression to the reader of what tropical soils really are like. Those who have been out and who have seen them will recognise the picture and appreciate the details supplied by so good an observer; those who have never seen them

will be enabled to visualise them better than would otherwise be possible.

Tropical agriculture already plays a great part in our national life. It supplies some of the essential factors in our modern civilisation: mundane necessities like vegetable oil, cotton and sisal, sugar; and amenities such as tea, coffee and chocolate. In the near future it may well play an even more important part, for on its development will largely depend the future of the tropical regions of the earth and of the numerous and sometimes virile peoples living there. Agriculture is the most visible and permanent interest in their lives; it has for them an importance vastly greater than most English people would think possible, and it may yet be the factor which will determine the relationships of the white and the native races. Of all the difficult problems confronting mankind none is more urgent than that of finding some way in which the races that cannot fuse may still live together in peace and harmony.

E. J. RUSSELL

ROTHAMSTED EXPERIMENTAL STATION,
HARPENDEN, *September* 1932

PREFACE

THE present introductory account of tropical and subtropical soils is the outcome of twenty years' work in Africa and Asia, where the subject was studied both from its theoretical and practical aspects. The book is primarily intended for the planter, who, in spite of a sound training at home, soon finds himself faced by soil problems of an unexpected kind. Research stations within the hot zones are being multiplied, but, owing to the large distances involved, it still remains both difficult and expensive to obtain technical advice. The chief purpose of this book, therefore, is to assist the planter to solve his own problems.

The properties of soil cannot be understood without knowledge of their fundamental interrelation. This and its practical application have received special attention, necessitating an incursion into theoretical ideas. It is to be hoped, however, that this thorny path will lead to valuable practical results, since, after all, every correct theory is practical experience reduced to its simplest formulation.

In the second place, the book is intended for students of tropical agriculture. It supplements existing works on soil science by giving greater prominence to those special problems of the tropics

which are too briefly treated in general textbooks. It is in no sense a final work of reference, but should serve as a starting-point for individual observation and deduction, which are even more essential in the immature science of tropical pedology than in temperate climates.

P. VAGELER

BERLIN, *January* 1930

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INTRODUCTION

Although the *Monographien zur Landwirtschaft warmer Länder* constitutes a series of reliable manuals on the cultivation of tropical crop plants, there has hitherto been no good book on tropical and subtropical soil science. We are therefore the more fortunate in that Dr. Vageler has now written such a book. Dr. Vageler is peculiarly qualified for his task from both the scientific and the practical sides. Much work in soil research stations, both in Germany and elsewhere, has given him an exceptionally sound scientific equipment, whilst many years' residence in the different climates of the tropical and subtropical zones has made him fully acquainted with their systems of agriculture.

His book, although primarily intended for the planter and for students of tropical agriculture, will prove of great interest also to all who are engaged in the increasingly important field of soil science.

Dr. Vageler bases his account of the genetical interconnection of the several soil types on personal observations. Much of it is new; the whole ordered survey of the genesis of tropical and subtropical soils will have a direct appeal to soil scientists.

His conclusions culminate in recommendations as to soil management and the choice of soil for

the various crop plants. These recommendations will be of great value to the planter.

This book will, I hope, receive the widespread recognition it deserves.

O. LEMMERMANN

BERLIN-DAHLEM,
April 1930

CHAPTER I

PROBLEMS OF TROPICAL PEDOLOGY

PEDOLOGY, considered as an independent science, is largely based on the study of soils lying within the temperate zone. This is due to the fact that until recently research stations were concentrated in temperate regions. Tropical and subtropical soils were, of course, submitted to examination whenever possible, but for the most part it was merely a question of odd samples collected by explorers who had insufficient technical training for the purpose. On the other hand, the investigator who examined the samples had, as a rule, no personal knowledge of tropical conditions, and derived little pertinent information from the accompanying field notes, which were often scanty and sometimes almost useless. It is only within the last twenty years that soil research in the tropics has maintained contact with local conditions and plantation practice and has based itself on the actual observation of soil structure in its natural state. Egypt and the Sudan, some American States and, notably, the Dutch East Indies are to the fore in this.

These researches were carried out on fresh soil material and paid increased attention to local conditions. They very soon showed, first, that views founded on certain European investigations as to the regional distribution of soil required considerable modification and extension when applied to

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These researches were carried out on fresh soil material and paid increased attention to local conditions. They very soon showed, first, that views founded on certain European investigations as to the regional distribution of soil required considerable modification and extension when applied to

the tropics, and, second, that many general principles valid for soils of temperate climates could not, even when modified, be transferred to soils of the torrid zone. The contrary opinion had long been held and occasioned confusion and not inconsiderable monetary loss in agricultural development. Traditional views as to the soil's calcium content, for example, are wide of the mark in the humid tropics. Many soils of the red earth class, which covers by far the greater part of the hot zone, contain practically no calcium carbonate and, if judged by ordinary standards, would show a very high lime requirement. In point of fact, however, this is not the case, and for certain crops, such as tea, which cannot stand lime, some of the soils actually contain far too much calcium and need artificial acidification. Other tropical soils, which under cultivation have proved rich in phosphoric acid, would appear deficient in this respect when examined on the basis of temperate soils. Heavy tropical soils which in regions of heavy rainfall form excellent cultivable land (as, for example, in Java, where they hold the world's record for yield of sugar) would be graded as uncultivable land by a classifier working on experience in temperate climates. Mistakes of this kind have actually occurred.

Again, whole groups of soils have no analogues in temperate regions. An instance of this is provided by the peculiar clays which result from decomposition of plagioclase rock in wet tropical climates. These have a strongly marked jelly-like texture, and frequently exhibit the original crystal forms of the minerals of the parent rock. It is open to question whether these formations, which are by no means rare, should be regarded as soil or rock. Any soil expert familiar solely with temperate conditions would reject the possibility that any crop could grow on this practically air-free mass. Never-

theless, on slopes there are very productive plantations of which the immediate subsoil has precisely this appearance. The reason for this is that in these seemingly uncultivable soils evolution of carbon dioxide from roots (more particularly of leguminosae), together with drainage, brings about dehydration of the soil colloids so that in a few months or even weeks a good cultivable soil is formed.

In the tropics, simple working and aeration of acid soil commonly produce big reductions in exchangeable acidity and in hydrogen ion concentration, whereas in temperate climates such changes are unknown. So also there is no parallel for the very high degree of acidity of good cultivable land, which is commonly observed in the tropics and has no harmful effect on the plants.

It would be easy to add to this list of peculiarities in tropical and subtropical soils, but these few examples are sufficient to show how wide a field for research lies open to the worker in tropical pedology.

To trace the characteristic features of tropical soils to the action of special factors would, of course, be wrong. In the main the same general laws as to the working of climatic factors on a given parent material hold in the tropics as in temperate climates: the same heat, light, water and air are at work in both places. What is materially increased in the tropics as against temperate regions is the intensity of climatic action considered in respect to duration and degree. As regards duration, one must bear in mind that in the tropics there is no winter to interrupt the course of soil-forming processes.

It must not be thought that soil workers who were engaged in the study of tropical conditions neglected to make due allowance for increased intensity of climatic action in considering the formation and classification of soils. The trouble was that these computations often outdistanced observed

fact; they were extrapolations, and as such were liable to serious error increased by irregular dependence of soil on locality. The investigators were not, however, to blame for the poor agreement between conjecture and fact which was so often evident in the study of tropical soils. In the history of science discrepancies of this kind are by no means rare whenever, as was the case with pedology, opportunity for personal observation is lacking. Thus, for instance, the luminescence which accompanies the passage of an electric current through rarefied gas was in no way to be inferred from the behaviour of gases at ordinary pressure. Again, the properties of all substances at extremely low and extremely high temperatures could, in default of special experiment, be predicted only to a rough approximation. Always and without exception extrapolation to extreme conditions, though invaluable as a guide to new research, has proved only partly correct.

Now, in comparison with those of the temperate zones, tropical conditions are extreme conditions. In hot climates temperatures are higher by 10°-20° C., and all chemical reactions proceed at from twice to four times the speed usual in temperate climates. In some cases the changes are affected by rainfall, which in the humid tropics may be twenty or thirty times the figure for central Europe. Conditions like these are in themselves sufficient to account for the fact that freshly formed products of different kinds of weathering occur in the humid tropics as deep profiles with undisturbed horizons and situated on the parent rock. Thorough investigation of such formations is of fundamental importance in respect to some general problems of pedology.

On the other hand, drought, either continuous or extending over many years, in conjunction with extremely high temperatures and with extremely high variations of temperature, makes wind an

important factor in soil formation. Striking evidence of this is shown by the wind-blown soils, often hundreds of yards thick, which fringe the deserts. It is difficult to give due weight to this factor without having encountered the tropical and subtropical dust storm which, in the course of a few hours, may form deposits some feet in depth and completely change the appearance of the landscape. No theoretical account, however precise and well considered, gives an adequate idea of the real effect of such a storm.

Turning now to the question of determining the manurial requirements of soil, we find more and more reason to regard field trials, which were long considered the sole reliable test, as having notable defects. Apart from the fact that the field trial always produces results *post festum*, *i.e.* one year too late, we have the constant stream of brand-new methods for evaluating experimental data. This indicates that one cannot treat as random variations those systematic errors, or rather those individual differences between control plots, which arise from variation of the soil within the experimental area, without reaching conclusions which are materially false. No serious investigator now supports the first enthusiastic claims which were based on the apparent precision of figures obtained by applying the theory of probability to plot technique, nor would he guarantee even his best experimental results as quantitative directions for practical manuring. In comparison with the information to be derived from statistical examination of large-scale trials he would treat his researches merely as the basis for fairly sound manurial recommendations. To arrive at such fairly sound recommendations by means of field experiments often entails a heavier outlay of time, labour and money than is justified by the result.

There is, then, good reason for treating the manurial experiment, whether large or small, simply as a test of the results of soil analysis, a purpose which it admirably serves. The manurial requirements of soils should be roughly gauged by quicker and cheaper methods so that the farmer or planter gets his information just when it is needed, *i.e.* before he plants his crop. This even holds good for most annual crops of the temperate zone, where manurial trials demand comparatively little time and labour, and where by reason of the large number of individual plants per plot one can, as a rule, avoid glaring mistakes. For tropical crops the position is still stronger. Here we are primarily concerned with trees or shrubs, *i.e.* perennial crops, whereas, with the exception of cotton and sugar, annuals are of less importance. Here large areas contain relatively few individual plants, which often spread their roots ten or twenty yards all round. The roots may also go down several yards or even to depths running into double figures where the soil is light. It is clear that in the case of such crops, unless one is prepared to lay down research plantations, one is practically debarred from replicated plot experiments. Guard strips may be provided, but one can never be sure which plant has actually received the manure. Again, owing to the depth of the root system, it may be years before the manure is evenly distributed, and in consequence the experiment must be repeated time after time before any result appears. Furthermore, as time passes, the plantation as a whole undergoes change, and it is often difficult to decide how far a final success is the result of manuring and how far it is due to natural development. One can indeed readily understand that in patchy districts practically every tree stands on its own particular soil, probably differing from that of neighbouring

trees. Besides, since the number of plants under observation is small, differences between individual trees have an unduly large effect and may occasionally give an entirely false impression. It is not surprising, therefore, that manurial trials on small plots have seldom given satisfactory results in the case of perennial tropical crops. There is, then, urgent need for establishing as an alternative to field trials some rapid and reliable means of ascertaining manurial requirements. For this purpose soil analysis or, more generally, soil science is obviously the only safe guide. As a matter of fact notable successes have already been achieved in the tropics by application of methods similar to those used in temperate climates by Neubauer, König-Hasenbäumer and Lemmermann. In this connection special acknowledgment should be made of Lemmermann's system for evaluating the relative solubilities of plant foods. Observations supported by practical experience and, in particular, data collected by research stations of the Dutch East Indies have now definitely established that statistical treatment of soil analyses provides an estimate of manurial requirement which is adequate for practical needs, although, of course, much has still to be done in clearing up this complicated problem.

Another problem which demands intensive study is the investigation of humus as formed in tropical and subtropical soils. The last ten years of pedological research have drawn attention to the surprisingly wide distribution of tropical swamps, which frequently differ from those of the temperate zones. Except for these swamps and for occasional and shallow forest mould one must admit that neither in the tropics nor in the subtropics is there much sign of humus. The bright colours of iron and sometimes of manganese compounds mask

the humus coloration not only in the subsoil but also in the surface layers of the profile. This has led to the view that tropical soils are notably low in humus, and that there is no need to bother about humus and no danger in destroying humus by intensive cultivation and clean weeding. Seldom have appearances led to a more mistaken conclusion. In the first place, the humus content of soil in tropical climates, especially in regions of heavy rainfall, is by no means low, and in the second place, humus is just as important a factor in conditioning tropical land as in temperate climates. This was shown by careful and extensive experiments in the Dutch East Indies, where in many cases introduction of heavy green manuring has saved the crop and has proved essential to economic production. In some cases humus is more important in the tropics than in temperate climates, since certain crops, such as cinchona, coffee, etc., have facultative and perhaps obligatory fungoid roots (mycorrhiza) which only develop in presence of humus.

From the practical point of view special interest attaches to all investigations into the relations between the physical and chemical properties of soil and its natural vegetation. Such enquiries help to answer the question whether, and to what degree, one can use natural vegetation as a practical guide to soil fertility. Every step in this direction is of value to the agricultural pioneer who opens up virgin land and usually finds his first problem to be the choice of a suitable area. The development of tropical and subtropical countries lacks the wealth of accumulated experience which in temperate regions enables the farmer to form a fairly shrewd estimate as to the productive possibilities of the soil he sees before him. A judicious choice is, however, more vitally important in the tropics than it is

at home. Many tropical crops will not grow at all unless the soil has certain well-defined properties, and in consequence the whole system of farming and the selection of crops depend on the choice of soil and vice versa. Even when the choice as to the kind of soil has been correct, there remains the no less important question of its richness.

One must bear in mind that the well-developed transport system and comparatively small distances of the old agricultural countries make it easy for the farmer to overcome some deficiency of plant food by application of artificial manures. Cultivation costs are certainly increased when such measures become necessary, but they rarely exceed the economic limit. Colonial lands, however, lie thousands of miles from the source of artificial manures, and long distances and defective communications so increase the freight that an attempt to utilise poor land which needs heavy manuring is doomed from the start. On the other hand, in rich soil heavy manuring may prove highly profitable owing to the big return. As a rule, even when poor land is first brought under cultivation, profitable yields are obtained, since reserves of plant food have been gradually built up during hundreds or thousands of years of fallowing. It is only with the third or fourth crop that the catastrophe occurs, *i.e.* just when an initial success has led to considerable outlay in extension of the undertaking. Weighty evidence of this is found in the numerous abandoned plantations of colonial countries.

It is hardly too much to say that more than 75 per cent of all failures in tropical and subtropical countries are due to the choice of unsuitable land. In some cases the soil cannot support the crop owing to the high cost of cultivation and machinery; in others excessive poverty of the soil, accompanied by feeble response to manures, necessitates too

heavy expenditure on this head. In either case the soil should have been left to its original forest or steppe.

The "inexhaustible richness of tropical soils" is but seldom found in Nature and demands of the seeker painstaking attention to the teachings of practical and scientific experience. If ever appearances are deceptive they are so in the tropics and subtropics, and only thorough training in study of the soil can save the planter from grave errors which cause him or his backer to lose their money.

CHAPTER II

ROCKS AND MINERALS CONSIDERED AS THE PARENT MATERIAL OF SOIL AND IN RELATION TO SOIL FERTILITY

During the first half of the nineteenth century the older agricultural literature, when dealing with soil, was dominated by the so-called "humus theory" originated by de Saussure and strongly advocated by A. Thaer. In their view humus alone was of value, whereas mineral constituents were of no chemical significance and had only minor importance in respect to the physical properties of a soil. It is only in the geological and chemical literature of that period that one finds occasional investigations which use the geological, or rather the petrographical, origin of soils as a means of classification and as a guide to soil fertility. Davy, for example, in his *Elements of Agricultural Chemistry*, writes as follows: "When the earthy portion of soil seems to consist of decomposed material derived from some particular kind of rock one may describe the soil by the corresponding adjective, for example, basaltic or granitic soil".[1]

[1] The original passage reads as follows: "In cases where the earthy part of a soil evidently consists of the decomposed matter of one particular rock, a name derived from the rock may with propriety be applied to it. Thus, if a fine red earth be found immediately above decomposing basalt, it may be denominated basaltic soil. If fragments of quartz and mica be found abundant in the materials of the soil, which is often the case, it may be denominated granitic soil; and the same principles may be applied to other like instances." (1846 edition, p. 125.)

While under the jurisdiction of geology, which disclosed the origin of the soil but had no practical bearing, soil science gradually fell into disrepute among farmers. Even the coming of Liebig and a realisation of the importance of the inorganic constituents of soil did not induce co-operation between the agricultural and geological schools, although these sometimes attacked the same problems from their separate view-points. The sole interest of the petrographers and geologists lay in the weathering processes of rocks and minerals and in comparing the original material with the product which was often also studied as rock in the making. The fact that the product of weathering had agricultural properties was dismissed as incidental, and an attempt was made to classify soils on a geological-petrographical basis. This scheme completely failed to cope with the complex problems presented by soil. Another notable failure was that of attempts to establish a purely geological classification. To-day these seem almost incomprehensible, for although the composition and properties of soils regarded as products of rock weathering must be primarily dependent on the parent rock, yet the various rocks of the earth occur in almost all the different geological epochs with small variations characteristic of these periods. It follows that the rocks of all epochs, when decomposed by weathering, must yield more or less the same soils, a conclusion which demonstrates the untenability of the purely geological system of classification. That the system nevertheless contains a grain of truth will be shown below.

Complete rejection of the geological-petrographical system of soil classification does not, of course, imply that almost all work treating soil from this point of view is valueless. Precisely the opposite is the case. The great body of positive knowledge as to

the distribution of different types of soil and many important and fruitful points of view and methods used in modern soil research are derived from the exact work of geological surveys in different countries, and it is increasingly clear that the practical significance of these contributions is by no means exhausted. This explains why, in spite of admitted failure in the important problem of soil classification, the Geological Institutes of Germany as recently as 1908 explicitly recognised pedology as a subdivision of geology and recommended that it should be taught exclusively by geologists. Meanwhile, however, pedology had at last been born as an independent science.

It was not chance that Hilgard, an American, was one of the first soil workers to perceive that one of the weightiest factors in soil formation was not climatic agencies considered as a whole, but local differences in climate which find characteristic expression in the trend of weathering phenomena, and finally in the properties of the developed soil. To arrive at this fundamental conception of regional pedology required actual observation of broad differences of this kind, and at a time when opportunities for international travel were limited, the huge continent of North America, which contains within a single political unit almost all variations of climate from polar to equatorial, was bound to present these features and to suggest this point of view. Ramann and Glinka founded modern regional pedology on a firm basis by developing the idea that climate and parent rock were jointly at work in soil formation. This conception will undoubtedly continue to be the starting-point of all genetical work as to the formation and distribution of soils, but from the practical point of view it is still inadequate. The completion and working out of regional pedology from the practical side—applied soil science—still

has a very weak footing; in certain directions, one may say, it is completely lacking.

Many soil workers of the agricultural school are secretly of the opinion that to the farmer the genetics of his soil are a matter of absolute indifference, since he sees no connection between these considerations and the activity and condition of his land. E. A. Mitscherlich, for example, represents many agricultural chemists when he says, somewhat obscurely, "It does not matter to our crop plants by what geological process the soil on which they grow was originally formed". One may seek in vain in the writings of those who study soil simply as agricultural chemists even for a hint that either petrographic geology or mineralogy is of practical value in soil work. In writings of a less definite bias one may certainly find, at any rate in the case of standard textbooks, an admirable exposition of the petrographic point of view, while mineralogy and petrography are officially recognised as sciences collateral with agriculture. I cannot, however, call to mind that any practical use was made of this view-point for soil valuation even in the works that go farthest in this direction. The acquaintance is more or less Platonic and does not exceed friendly tolerance.

In point of fact, are the agricultural chemists right in thinking that in respect to practical soil problems one may more or less ignore the petrological-mineralogical point of view, to say nothing about the geological standpoint? Is the mineralogical composition of soil and the petrographic character of the parent rock, and, finally, is the geological age of these rocks really so remote from practical questions as the agricultural chemical school of soil science assumes? Are indeed the colloid substances of soil and their interactions alone of importance?

No one will deny that the soil colloids are of decisive importance as carriers of the actual and existing properties of a cultivated soil and as factors in crop production. It may indeed be said that the progress of research will not improbably give even greater significance to the soil colloids than is already attached to them. This, however, in no way constitutes a judgment on the value of soil minerals. For except when they are of organic origin, all these colloids, which are the chief factors in all soil reactions and which compete with plant roots for foodstuffs present in the soil, are derived from soil minerals. From soil minerals too the plant foods are ultimately derived.

These minerals are accordingly to be regarded as the providers of all important substances in the soil. Their amount and kind, so far from being of negligible practical significance, must be of very considerable moment in assessing soils, for these minerals form the reserve and raw material of plant foods. It is very easy to see why this rather obvious line of thought has achieved so little in soil research and soil valuation and has indeed hardly received serious consideration. In cold and temperate climates the feeble activity of climatic agencies is for a considerable part of the year still further restricted by the winter months, and accordingly the course of weathering processes is so slowed down as to require tens or even hundreds of years before revealing to the soil worker any definite change in the mineral reserves of the soil. On the other hand, many observations have been made of weathering in rocks where purity of material and ease of inspection permit the detection of very small changes. All attempts to use rich rock materials for immediate conditioning or manuring of soil have had very poor results under temperate conditions—a circumstance to which the superphosphate industry

owes its existence. Every failure of this kind inevitably strengthened the view that soil minerals had no practical importance and threw discredit on the whole geological and petrographical approach to the valuation of soils. Here again soil workers forgot that the temperate zones of the globe are far from representing the whole land area, but are, in fact, quite a small part of it. Europe, in particular, is unusually uniform in climate and is no more than a small and rather oddly shaped peninsula of the continent of Asia. In neglect of this fact, soil workers generalised the observation that under European conditions it is regularly found that fresh minerals weather comparatively slowly in the soil and have therefore very limited practical importance. This would never have happened had the question been considered in relation to the earth as a whole.

It was emphasised in the introductory chapter that, by reason of the 10°-20° C. increase in mean temperature of the tropics and subtropics (to say nothing of maximum temperature), together with rainfall which can be very heavy, all chemical processes occur with increased intensity in the soils of the hot zones. If one bears in mind that there is no interruption by winter, one will hardly err in estimating that over the whole year and in relation to temperate climates the intensity of weathering in the tropics is increased at least tenfold. This means that the centuries required for weathering in temperate and, *a fortiori*, in cold climates shrink in a hot and wet climate to so many decades, decades shrink to years and years to months. Changes in the mineral part of soil and effects which in temperate climates are discernible only at great length of time must accordingly manifest themselves comparatively quickly and so acquire overwhelming practical importance. Just as ruins in the tropics,

if not specially maintained, disappear beneath the almost visible growth of rank vegetation, so also mineral fragments decompose fairly speedily in tropical soil, as was shown by the informative researches of Mohr in the Dutch East Indies. These minerals continuously form soil colloids either as residues of decomposition or by actual synthesis, and they continuously release not inconsiderable quantities of plant foods especially when cultural operations still further hasten the process of weathering.

The barrenness of very old volcanic ash deposits in northern regions is impressive. Many years after the latest fall only the lowest forms of life establish themselves in the loose dust, whose mineral constituents are almost as fresh as at the eruption. In the humid tropics, on the other hand, vigorous vegetation clothes the devastated slopes in a fraction of the time required for the scantiest signs of life in the north. A few decades suffice to convert the barren ashes to fertile soils admirably suited for human settlement, and, as may be seen in the East Indies, rejuvenated from the pedological point of view by the deposits of volcanic ash.

The mineral part of soil, which in temperate climates is little more than the soil skeleton in a physical sense, becomes in the tropics and subtropics a constant reservoir not only of plant foods but of soil colloids which carry the foods. Moreover, both foods and colloids are set free in fairly liberal amounts. A correct estimate of the amount and kind of these mineral reserves thus serves, as was first demonstrated by Mohr, to measure the permanence of soil fertility, and in hot climates is accordingly a factor of more than secondary importance in assessing soil value. This importance is increased by the fact that cultural operations affect the decomposition of soil materials to a much

higher degree in tropical than in temperate climates, with the result that the mobilisation of plant food reserves is much more rapid. This helps to explain the excellent results obtained in the tropics by application of raw phosphate, which is often as effective as superphosphate.

The breaking up of rocks into their constituent minerals under the influence of weathering is largely dependent on the rock structure. This, together with the whole type of exposure generally, though not always, differs according to the different geological epochs to which the rock belongs. Differences in rock structure lead to differences in the rapidity with which climatic factors act on the raw material, and differences of exposure, as we shall see below, can produce differences in the soils derived from a single kind of rock. This is particularly noticeable in the case of soils which have not suffered transportation, *i.e.* the so-called eluvial (also sedentary, residual or primary) soils which occupy a comparatively wide area in the tropics and subtropics where disturbance due to the ice ages is hardly appreciable. It follows that the geological age of rocks has a certain though secondary importance.

Of primary importance is the consideration that the permanence of fertility in a soil varies with its content of minerals which are still liable to decomposition. A soil having a high content of such minerals is, other things being equal, better than a soil with no mineral reserves. We may therefore conclude that knowledge of the chief minerals and rocks, which have formed a soil and which by the process of weathering provide its plant foods, is of great value to the practical farmer in the tropics and subtropics, although his professional colleague in temperate regions neither has nor needs this information.

I. THE MOST IMPORTANT SOIL MINERALS

When one speaks of important or most important soil minerals, the expression requires close definition, for minerals can be important in respect to the study of soils in very different ways.

In the first place, a soil's content of minerals may indicate its origin in a certain kind of rock if they approximately correspond to the mineral constituents of any one rock. In this sense soil minerals are important as affording a historical survey of the formation of the soil, and this is especially the case when new compounds accompany the original or primary rock residues and so indicate how long weathering has been at work. This indicates also a rearrangement of important constituents from which inferences may often be drawn as to the general properties of the soil. Of this, the tropical group of red earth soils presents a striking example, for there the appearance of secondary iron and aluminium minerals is usually a sure sign that the soil is already impoverished and that, as a rule, all phosphoric acid is fixed in a form almost unavailable for plants. That consideration of these features is of moment in the choice or valuation of land requires no emphasis.

In the second place, as we have already seen, the value of soil minerals consists in their contribution of inorganic soil colloids and of plant foods or, in exceptional cases, of substances harmful to plants, as, for example, free sulphuric acid, in which case, of course, their value is strongly negative, and should be specially noted.

In order to estimate the reserve of plant foods or of toxic substances it is important to make an approximate estimate of the amounts in which the various minerals occur, although this is not always necessary in order to form an opinion as

to the genetic relations of the soil. The fact that soil minerals are of pedological importance from both points of view does not, however, add to the number of minerals which it is necessary to determine; on the contrary, it very considerably reduces the number. For in regard to the second point only those minerals can be of importance to the agriculturalist which are present in considerable amount, that is, not less than 1 per cent of the soil mass, for they do not consist of pure plant foods, but merely contain a certain percentage of plant foods. From the genetic standpoint, on the other hand, it is chiefly the secondary minerals which are important as indicating the age of the soil. The exact determination of the parent rock requires tedious and precise identification of the so-called accessory characteristic minerals occurring in minute amount, and this problem is not within the scope of practical pedology.

In practice a working knowledge of quite a limited number of minerals is sufficient for an adequate mineralogical specification of all soils, and this any soil worker can acquire if he puts his mind to it and does not underestimate the actual difficulties by reason of the apparent simplicity of the problem.

The most important soil minerals are:

(1) Quartz, a chemically inert and therefore harmless constituent.

(2) Volcanic glasses (3) Felspar and felspathoids (4) Mica (5) Amphibole and pyroxene (6) Carbonates, dolomites and gypsum (7) Minerals containing phosphorus (8) Primary iron and titanium minerals	Primary minerals.

(9) Secondary minerals and the most important small concretions.

(*a*) Simple Methods of Investigation

In order to avoid misunderstanding it is important to state that in speaking of soil minerals we are concerned only with those minerals which are included in the fine soil, *i.e.* in the fraction of soil of which the particles do not exceed 2 mm. in diameter and which is obtained by rubbing the soil through a 2-millimetre sieve. The coarser fraction which in the International classification is graded as stones (diameter exceeds 2 cm.) and gravel (diameter between 2 cm. and 2 mm.) does not usually consist of single minerals but of rock fragments, and can be investigated later. On the whole, tropical soils with a few exceptions contain a very small proportion of stones and gravel; one may often search in vain over thousands of square miles for a single occurrence of these coarse fractions which in the soils of temperate climates often play so important a part. When the fine soil obtained in this way is examined by the naked eye or under low magnification, in most cases it shows at once a characteristic which is common to most subtropical soils (other than pure quartz sand), and almost invariably present in tropical soils of the humid and semi-humid zones, but which is absent from or very faintly evident in temperate soils. In the first place, the crumbs of soil stick so closely together that they sometimes appear to be tiny rock fragments, and have been appropriately labelled pseudosand by Deuss, and, in the second place, almost every mineral fragment has a coating, thin or thick, which largely consists of iron hydroxide and entirely prevents identification of the mineral. This characteristic is found in most tropical

soils and is specially pronounced in the red earths.

To make mineralogical investigation possible the soil accordingly requires preliminary treatment which separates the soil grains and at least partially removes the covering film. This treatment consists in the peptisation of the aqueous soil suspension by means of ammonia or, perhaps better, by sodium carbonate solution as recommended by the Gordon College in Khartoum. When this does not succeed, treatment with 10 per cent hydrochloric acid should be tried, in which case one must guard against dissolving not only the covering film but also all carbonates. These, if present in quantity, will produce effervescence or bubbles of gas.

Mineralogical investigation may be limited to the fractions of coarse sand (2·0-0·2 mm.) and fine sand (0·2-0·02 mm.) which are obtained in the course of mechanical analysis, for the still finer fractions are difficult to determine and, moreover, consist of colloids, together with a larger proportion of minerals very resistant to decomposition, quartz and glass dust in many cases, which are for this reason of minor significance for practical soil study. Beneath the microscope—for choice a binocular microscope of medium magnification—the well-mixed coarse and fine sands of the soil usually present so diverse a display of all possible mineral fragments that some general scheme of separation is required before one can think of estimating the individual minerals. This separation can be satisfactorily achieved by a specific gravity method for which the Agrogeological Laboratory of the Buitenzorg Station for Tea Research, Dutch East Indies, has worked out a method which is simple and quite sufficiently accurate for practical needs.

The mixture of minerals, in amount not exceeding 5 grammes, is first thoroughly dried for one hour at

105° C. in order to dispel moisture which would interfere with the separation. This mixture is then stirred with about 25-40 c.cm. bromoform of sp. gr. 2·9 in a small funnel having a wide tube, to which is attached a rubber tube about 10 cm. in length and closed at the bottom by means of a clip. The mixture is gently agitated for about fifteen minutes, by which time the heavy minerals have settled into the rubber tube. Care should be taken to avoid spilling bromoform on the fingers, since contact with it produces a very troublesome eczema on sensitive skins, the irritation lasting for several days, while with certain persons symptoms of fever are also felt.

Sedimentation is complete when no more particles are seen to sink on stirring the mineral mass. A feather policeman is then used to transfer to the tube any minerals which have settled on the sloping sides of the funnel, and a second clip is applied to the top of the rubber tube. The liquid enclosed between the two clips, together with its content of minerals, is then transferred to a large watch-glass. This fraction, which we shall call Fraction A, includes all minerals of specific gravity over 2·9. Of such minerals those of interest in soil work are as follows:

Table I

Dolomite and aragonite.
Fresh magnesia mica.
Amphibole and pyroxene.
Primary and secondary iron minerals.

Accessory or rare minerals of secondary importance also occasionally present are:

Magnesite.
Tourmaline.
Almandine (iron garnet).

Rutile.
Anatase.
Zircon.
Apatite. (Very exceptionally isolated by this means.)

The contents of the watch-glass are dried on the steam-bath for a few minutes and are then weighed, giving the percentage content of Fraction A. As a rule it is sufficient merely to separate this fraction into amphibole and pyroxene on the one hand, and into iron minerals on the other. This is very conveniently effected by means of a good horse-shoe magnet. A rough estimate of the relative amounts present is quite enough for practical purposes. The residue remaining in the funnel is washed on to a big clock-glass by means of benzene, dried and agitated as before in a mixture containing chloroform (19-20 per cent by volume) and bromoform (80 per cent by volume). This mixture has a specific gravity of 2·6 and accordingly deposits all minerals of sp. gr. 2·6-2·9. After sedimentation the tube contains the following (Fraction B):

Table II

All plagioclases.
Quartz.
Potassium mica.
Weathered magnesia mica.
Calcite.
Chlorite.

A third fraction (Fraction C) remains suspended in the funnel: it contains—

Table III

Orthoclase.
Leucite.

Nepheline.
Gypsum.
Volcanic glasses.
Products of weathering (pseudosand) and secondary minerals (other than iron minerals).

The fractions are dried, weighed and then examined under the microscope for their content of single minerals, which are estimated by the area they cover in the field of the microscope. It will be understood that analysis of this order makes no claim to absolute precision. This, however, is by no means requisite for practical purposes; what is needed is a sound general impression as to the mineral reserves of a soil, and that information is amply provided by the method now described.

For microscopic identification of the individual minerals one requires a polarising microscope and mounting liquids of varied refractive power. The determination is not possible without some training in mineralogy. Many agriculturalists working in the tropics and subtropics have, however, received this training, and the most important minerals can be identified by very simple tests, and it seems advisable, therefore, to review the distinguishing features of these minerals as they occur in soil. For practical determination under the microscope one may use the "Table for Determination of the most important Soil Minerals", which includes some of the less common minerals also. In this table (at end of this book) the index of refraction is taken as the most important character, while colour and crystal form and, in the case of doubly refracting minerals, angle of extinction are also used. The general procedure for determining the refractive index consists in embedding the mineral under investigation in drops of liquid placed on the platform of the microscope. The refractive index of the mineral is

thus found to lie between that of a less strongly and that of a more strongly refracting liquid. There will be little chance of mistake on this point if the Becke white-line method is used. Weinschenk justly remarks: "The determination as to whether the index of the crystal is higher or lower than that of the liquid is very simple. The cone of light is cut down until the contact between the crystal and the liquid or between two crystals appears as a sharp line, and then the objective is raised. A distinct band of light can be recognised parallel to the contact between the two mediums, and this moves towards the substance with the higher refractive index upon raising the tube, while the more weakly refracting object appears to have a dark border. Upon lowering the tube the opposite phenomenon is observed."[1]

The number of possible minerals is so reduced by the preliminary separation into Fractions A, B and C, and by ascertaining that the refractive index lies between two known values, that mistakes in the final determination are almost excluded. If a mineral cannot then be identified from the table it is very probable that identification is not worth while, since it can have no special significance in soil study.

(*b*) The most Important Minerals

(1) *Quartz*

Quartz, silicon dioxide, SiO_2, of which the metallic constituent, silicon, forms about 25 per cent of the upper ten miles of the earth's crust, is certainly a very widely distributed soil mineral, but nevertheless is not so common as one is inclined to assume. Comparatively few eruptive rocks are so rich in

[1] Weinschenk, *Petrographic Methods*, translated by Clark, 1912.

silica that it finally separates from the magma in the form of quartz. Quartz chiefly occurs in areas in which granite and diorite, quartz porphyry and quartz porphyrite, rhyolite and dacite, and finally gneisses and mica schist are found, or in which sedimentary rocks have been formed from such rocks and form a coating on the eruptive core. Over wide volcanic areas where the ejected material is basic, quartz is only found here and there where it has been formed by some secondary process.

In soils originating from fresh volcanic quartz-bearing rocks it is usually present in well-formed

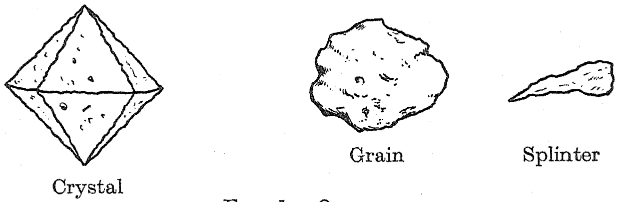


FIG. 1.—QUARTZ.

crystals which, as a rule, measure only a few millimetres or fractions of a millimetre, but are sometimes strikingly regular and measure 1 or 2 centimetres across.

When a high content of the graceful double pyramids of quartz is observed, there is at once a probability that the soil was formed *in situ*. Their occurrence makes it immediately advisable to make a close study of the depth of the soil profile since in such cases very unpleasant surprises are not uncommon.

In deposited soils where the soil material has been transported either by wind or by water, the crystals, as a rule and in spite of the hardness of quartz (H. 7), have usually undergone vigorous grinding and are reduced to round grains, many of which have been further broken into angular fragments showing conchoidal fracture. The transparent

quartz grains, which are colourless or have a gray, pink or blue tinge, show a very characteristic glossiness of surface, while small cracks and superficial depressions are filled with iron hydroxide. Much more commonly, however, the quartz grains are opaque and milky or yellowish white in colour. In the red earth soils quartz is almost invariably coated with iron hydroxide, which has, of course, to be removed before identification can be carried out.

As a rule the grains show no regularity of cleavage. Absence of this, a refractive index lying between those of eugenol and nitrobenzene, and the other characteristics mentioned here are a safe means of identifying quartz under the microscope.

That quartz by reason of its composition is merely soil ballast, *i.e.* is more or less chemically inert, and that it accumulates in old and impoverished soils needs no special emphasis.

(2) *Volcanic Glasses*

Most books on soil hardly mention volcanic glasses at all. Such a treatment does not, however, accord with the practical importance of these minerals. A glance at a geological map of the world will show that whole countries and vast areas are of volcanic origin. In the tropics and subtropics such regions, especially if of recent origin, have a content of volcanic glass which so far from being negligible is often their most important constituent.

Glasses are supercooled melts in which crystallisation proceeds so slowly as to escape human observation. They may be formed from any magma, and are so formed during eruption. Not only do volcanic ashes and sand and the tuff rock which is formed from them consist chiefly of glass, but many solid rocks display a glassy basis which, being more

or less unchanged magma, contains its full quota of plant foods. The so-called acid volcanic glasses are "clear as glass" or only faintly coloured. They occur as sharp-edged fragments and splinters often enclosing bubbles, in which case the material is usually pumice-stone and readily recognisable. Fragments which contain no bubbles may be identified by absence of double refraction, which is established if the specimen remains dark when rotated between crossed nicols. They resemble quartz in showing conchoidal fracture.

Their content of alkalies, calcium and magnesium is so irregular and varied that there is no object in giving mean values. These metals usually account for a few per cent of the weight, the main constituents being silicic acid and alumina. Phosphoric acid is almost completely absent from the acid glasses except for the rare cases in which the glasses enclose minute needles of apatite. Such specimens are immediately identified under the microscope. They occur but seldom, since apatite, or rather phosphoric acid, is one of the first substances to separate from a cooling magma and is therefore rarely present in the acid residual magma from which the acid glasses are formed.

Even in tropical climates acid glass weathers very slowly. As it breaks very readily, it is to be found in clay and silt, the finest fractions of mechanical analysis. Its resistance to decomposition makes it of low value as a reserve of soil minerals; it is indeed hardly superior to the chemically inert quartz. In spite of the fact that a total analysis of this kind of soil may show very considerable quantities of plant food, such soils are often very infertile after a short period of cultivation. When first opened up they have a mobile capital of plant foods which suffices for a few crops, but lack of staying power makes them a dangerous investment.

With the dark basic kinds of glass it is quite a different story. The colour of these basic glasses varies from brown and dark green almost to black, and is chiefly derived from iron compounds which are readily oxidised and thereby make it easy for climatic factors to act on the glass. Since decomposition is rapid, basic volcanic glass is to be found mainly in the coarser fractions of soil except in the case of very recent volcanic areas, in which big lumps of obsidian (acid glass) abound. The clay fraction usually contains none, since here the vulnerable superficial area is so big in relation to the volume of the particle that the glass is no longer capable of resistance. Basic glass occurs almost without exception in the form of fairly sharp-edged splinters and irregular platelets showing conchoidal fracture. Bubbles and crystalline inclusions are common. Absence of double refraction characterises both basic and acidic glasses.

In the basic glasses the content of plant foods varies widely as in the acidic glasses; usually, however, it is quite considerable. The potassium content seldom falls below 2 per cent, while calcium and also magnesium seldom fall below 3 per cent. Inclusions of apatite which imply a considerable content of phosphoric acid are more common than in the acid glasses, but are nevertheless exceptional. The normal content of phosphoric acid is low.

Basic glass is a very important constituent of the mineral reserves in soil. The great and lasting fertility of many volcanic districts in which the magma is basic is in no small degree derived from the presence of basic glasses in the soil reserves. The Cameroon Mountains in West Africa, Kilimanjaro in East Africa, many volcanoes in Asia and Central and South America, are examples of this productiveness which, as explained above, depends not only on the considerable amounts of plant food

present in basic glass, but also on the readiness with which they become available.

That one will look in vain for basic glass in light-coloured soils is evident, for not only are the basic glasses dark in colour and so impart a dark tinge to the soil, but also the oxides of iron which they liberate have a still stronger colouring action on the original material.

(3) *Felspar and Felspathoids*

(i) *The Felspars*

Of soil minerals which merit approximate estimation from a practical point of view, the felspars are the most important carriers of potassium and sodium, and contribute also to the calcium content of soils. They are characteristic constituents of almost all eruptive rocks and, consequently, of all sedimentary rocks apart from chemical deposits, and are therefore to be found in almost every soil. The value to be ascribed to their occurrence is variable and depends on which felspar is present, for the felspars differ not only in their content of plant foods but also in their ease of decomposition, which is even more important in building up the floating capital of the soil.

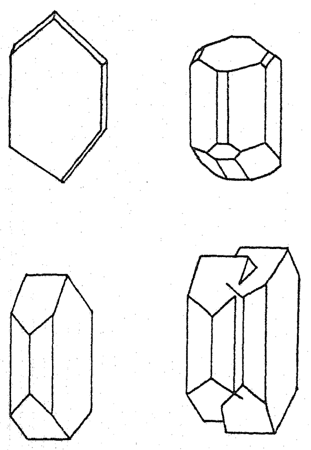
1. Potassium Felspar.—The varieties of potassium felspar differ chiefly in crystal form and in manner of occurrence; in chemical composition they are fairly evenly represented by the following figures:

SiO_2—64·72 per cent.
Al_2O_3—18·35 ,,
K_2O—16·93 ,,

The content of alkali, however, is liable to variation, for potassium can to some extent be replaced by sodium, as in sodium orthoclase, but even so the potassium content seldom falls below 7 per cent.

As a general average potassium may be taken at 12 per cent, the balance consisting of impurities, calcium, magnesium, iron, etc., which are merely accessory constituents and have no practical significance.

By far the most common felspar is orthoclase, which is a characteristic constituent of granite and gneiss and to a less degree of syenite, quartz porphyry, orthophyre, nepheline syenite and nepheline porphyry. The commonest crystal forms of orthoclase are shown in Fig. 2. Twin crystals greatly outnumber the single crystals, of which form "a" is of frequent occurrence. To judge from very numerous observations, orthoclase weathers fairly easily, the rate being largely dependent on moistness of climate. In arid and semi-arid tropical soils well-formed little crystals of orthoclase are to be found even in the fine sand, but sharp-edged fragments showing well-marked cleavage are rather more common. Here also the orthoclases are sometimes as clear as water. In moister regions the crystals or crystal fragments are mostly ill-shaped and dark as a result of incipient decomposition. They are largely confined to the coarser fractions, and especially to the stone and gravel fractions, of soil and are then usually embedded in quartz. The larger specimens are frequently flesh-coloured or reddish. In alluvial soils which have undergone long transport by water the orthoclases are usually, in spite of their comparative hardness (H. 6), ground beyond



[a] Twin

FIG. 2.—ORTHOCLASE.

recognition and appear as small rounded prisms and plates which are not to be identified without precise investigation.

Microcline, which has practically the same chemical composition as orthoclase, differs from it only by sometimes having a finer structure. Examination under crossed nicols shows this to be a consequence of the crossing of two systems of minute crystalline rods, for when one system is so placed as to be extinguished the other is clear.

2. THE PLAGIOCLASES.—Plagioclase, important in soil work, includes a series of mixtures of which the two end members are: sodium plagioclase or albite (SiO_2, 68·6; Al_2O_3, 19·6; Na_2O, 11·8 per cent) and calcium plagioclase or anorthite (SiO_2, 43·1; Al_2O_3, 36·9; CaO, 20·0 per cent). As the content of anorthite rises, the intermediate varieties, which are rather difficult to distinguish, are known as oligoclase, andesine and labradorite or bytownite. From albite to andesine are regarded as acid plagioclase and the rest as basic plagioclase, the distinguishing feature being the higher or lower content of silicic acid. This is of practical importance in that the acid plagioclases weather much less readily than the basic and, therefore, occur in soil in a better state of preservation. This same property discounts their value as soil mineral reserves, and a further disadvantage is the predominance of sodium, which, if present in excess, is no desirable constituent of soil.

The basic plagioclases are more valuable in virtue of their higher calcium content. Furthermore, they weather very readily to amorphous material, especially if attacked by carbon dioxide, whereas the acid plagioclases show a strong tendency to pass into secondary gel-like minerals, while maintaining their crystal form. This is specially marked in regions of very heavy rainfall and in the lower layers of soil.

The value of the plagioclases depends on potassium content as well as on calcium content. Potassium, however, is only accessory in its occurrence here, and its amount is accordingly very small, hardly exceeding 0·5 per cent on the average. On the other hand, the plagioclases are usually to be seen in very large amount in soil, and their small content of potassium gains considerable importance thereby.

The most important crystal forms of the plagioclases are shown in Fig. 3. The formation of twinned crystals is at least as frequent in the plagioclases as

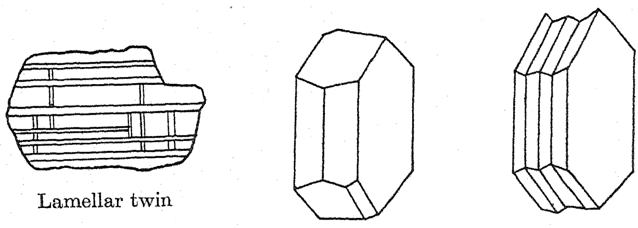


FIG. 3.—PLAGIOCLASE.

in orthoclase. Whereas the latter are, however, twin crystals in the strict sense of being built up from two-individual crystals, the plagioclase specimens are far more commonly polysynthetic twins and are composed of very numerous individual crystals. This type of occurrence is an excellent characteristic of the whole group.

When quite fresh the plagioclases are nearly colourless, and in fact the acid members are often so present in soil. Cloudy white and greenish tints with gray shading are, however, much more common, while in contrast to orthoclase reddish tints are unusual.

Differences in resistance to weathering shown by the various plagioclases correspond to their occurrence in different soil fractions. The pro-

perties considered above make it probable that only acid members of the group will be found in the finest fractions of soil. Big specimens falling in the stone and gravel fractions are as frequent as with potassium felspar.

It has already been noted that all felspars break down when transported by water. This is shown by the low content of felspar in widely transported soils, and also by a very interesting direct experiment undertaken by Daubrée. In this a journey of only 460 kilometres under water produced from 3 kilograms of mixed felspars 2·7 kilograms (90 per cent) of sludge, and of this 36 grammes showed all the properties of clay. During attrition 12·6 grammes of potash had passed into solution.

(ii) *Felspathoids*

The so-called felspathoids, nepheline, leucite and sodalite, are of importance in soil study since the two first occur locally in high amount, and since the last, together with the related nosean and haüynite, is no mean contributor to the chlorine and sulphuric acid content of soils.

Nepheline corresponds to albite in composition and, like albite, is of little value; it occurs in nepheline syenites, phonolites and nepheline basalts and in the soils derived from them. As it is of little practical value, although occurring abundantly, a mere mention is sufficient.

Leucite, on the contrary (SiO_2, 55; Al_2O_3, 23·4; K_2O, 21·6 per cent), is a potassium mineral which rivals or even outdoes potassium felspar in respect to high content of potassium and ready weathering under hot and damp conditions of climate. Fig. 4 shows the crystal form. Fresh crystals are colourless or white and often show a glassy reflection. Well-formed specimens are only to be seen in

regions of low rainfall. In wetter districts leucite occurs mainly in the coarse sand and sometimes in the fine sand fractions in the shape of well-rounded little grains with a dark surface and with rarely an edge showing. It is very easy to confuse leucite in this condition with opal, a widely distributed but, as far as soil is concerned, quite useless mineral. The wide difference in refractive power provides, however, a sure means of discrimination.

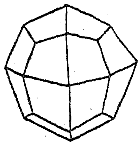


FIG. 4.
LEUCITE.

The minerals of the sodalite group, sodium aluminium silicates with admixtures of sodium chloride, sodium sulphate or potassium sulphate, occasionally occur in tropical soils. Their recognition, and indeed their occurrence, is but rarely of interest and need not concern us here.

(4) *Mica*

The micas are among the most easily identifiable and familiar soil minerals in regions containing eruptive rocks rich in silica or their derivatives. Their composition is more varied than that of almost any other mineral. The main constituents are silica, alumina and alkalies, which in the dark micas are accompanied also by magnesium and iron. These dark magnesia-iron micas or biotites are the most widely distributed members of the group and are, moreover, of special pedological interest, at any rate in hot climates. This limitation arises from the behaviour of the dark micas on weathering. In temperate climates biotite, which is probably formed by disintegration of felspar, has a high resistance to weathering. Thus one frequently finds in soils of temperate climates that "the dark flakes of mica have a clear border resulting from removal of iron and alkalies; often the iron is deposited

between the lamellae and imparts a reddish colour. Soils which are formed from rocks rich in magnesia-iron mica are clay soils rich in iron and are distinguished from soils derived from potassium mica by their physical properties and by their higher fertility" (Ramann).

Even so, as was shown by the experimental use of mica as a plant nutrient, weathering takes hundreds of years, and the supply of plant foods is proportionately slow. Mica flakes in the soil are often quite fresh or show merely the faint "false gold" coloration, while the percentage of strongly decomposed flakes is usually very small.

In soils of hot tropical regions, on the contrary, one can rarely establish the presence of fresh biotite even in comparatively recent soils. The false gold form also appears to be a relatively short-lived intermediate stage. In the great majority of cases even big complexes of mica are bleached not at the edges only but throughout, and have so little cohesion that they readily crumble to amorphous soil material, a sure sign that here the weathering process is fairly fast and of great practical importance. This impression, which is based on mineralogical analysis of the soil, is amply confirmed by study of soils and vegetation in micaceous areas which are of notable extent in Africa. If in the case of non-transported soils one compares those in which mica is unmistakeably present in the parent rock and in the surface layers with soils of low mica content, one finds that the former have a deeper red colour and decidedly darker shading than the latter. This feature often amounts to regular bands of dark and light soil which are particularly well seen from an aeroplane, when each streak of biotite-bearing soil, although washed out, shows clearly on the surface. Almost without exception the vegetation also is closer and

better developed, and this can only be a consequence of superior food supply.

The magnesia-iron micas show a markedly low resistance to weathering in all districts where arid conditions have led to high concentration of soluble salts in the soil. There, in contrast to neighbouring areas of low salt content, traces of biotite can be found only in minute amount or not at all, and weathering is always far advanced.

In any case biotite is a soil mineral of the greatest practical importance, for it is an indicator of soils well stocked with basic substances.

The composition of biotite is very variable. Milch gives as average values the following: SiO_2, 36·4; TiO_2, 1·15; Al_2O_3, 16·9; Fe_2O_3, 7·6; FeO, 14·6; K_2O, 8·15; Na_2O, 1·12; CaO, 0·88; MgO, 9·28 per cent. According to Ramann the potassium content varies between 5 and 11 per cent. Thus even in the least favourable cases biotite remains a notable source of potassium, and as it quite commonly contains in addition inclusions of apatite, the most valuable of phosphorus minerals, its value as a source of phosphorus should be kept in mind.

The identification of biotite as of the micas in general is simpler than that of any other mineral owing to perfect cleavage into the thinnest flakes which is shown even by strongly weathered fragments. The brilliant glitter of fresh or moderately fresh fragments is well known. Strongly weathered specimens have a whitish or yellowish colour and are often opaque under the microscope. The form of six-sided tablets with ragged edges remains common up to a late stage of weathering, when the separation of the flakes at the edges of the specimen shows up its constitution, leaving no doubt as to its identity. A diagrammatic illustration is given in Fig. 5.

A widely different value is to be placed on muscovite or potassium mica, which is usually transparent and has a silvery gleam. Its potassium content of 8-10 per cent is certainly higher than that of biotite, but it has an Achilles heel in respect to weathering in that no appreciable amount of iron compounds is present. Iron compounds greatly facilitate the decomposition of all minerals in which they occur by virtue of the strongly exothermic, *i.e.* energy-releasing, reaction $4\,FeO + O_2 = 2\,Fe_2O_3 + 36{\cdot}2$ calories. Owing to absence of iron, muscovite is very resistant even in hot climates. Even in the finest fractions of soil the thin platelets of the mineral

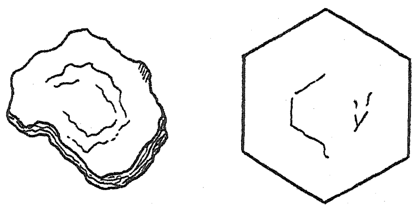


FIG. 5.—BIOTITE.

are to be found and are mostly quite fresh and transparent. The value of the mineral should not therefore be rated high. It appears, however, that in saline soils muscovite is liable to extensive decomposition.

For the sake of completeness chlorite may be mentioned here as a mineral frequently occurring in districts which contain chlorite rock. It has no practical importance, but may be mistaken for mica in a weathered state. In addition to silica and alumina it contains chiefly ferrous oxide and magnesia, of which the last is occasionally important. It occurs in soil as flakes having a pronounced greenish tinge, and is thereby readily distinguished from mica, which hardly ever has this colour.

(5) *Amphibole and Pyroxene*

The group of amphiboles and pyroxenes, also called the hornblende and augite group, is the most widely distributed of the mineral groups which are to be observed in soils. Hornblende and augite form two parallel series of salts of metasilicic acid with magnesium, calcium, iron and manganese, and probably differ in that the molecule of hornblende is twice as big as that of augite or of the pyroxenes in general. As the doubled size of the molecule is accompanied by a lessening of volume the amphiboles occur mainly, though not exclusively, in rocks which have been compressed by the weight of overlying mountains, as, for example, in hornblende schist, gneisses, granites and diorites. The amphiboles occur also in basalts and similar rocks. Pyroxenes, on the other hand, occur for the most part in basalts, dolerites and so forth, but are also often present in the rocks previously named.

The composition of the minerals lies roughly between the following limits:

Hornblendes	CaO, 10-20; MgO, 12-20; Alkalies, 1-5 per cent.
Augites .	CaO, 20-23; MgO, 13-16; Alkalies, nil per cent.

The hornblendes are accordingly more valuable than the augites by reason of their higher content of alkali. This higher value is unfortunately discounted by the fact that hornblendes show greater resistance to weathering than do the augites. In this respect both minerals display a characteristic which is not usually to be observed in other minerals. This lies in the fact that weathering proceeds not gradually but more or less in jumps. It is comparatively slow until uninjured individual crystals are affected by the weathering agencies. Once the apparently passive surface of the crystal is breached, either by chemical action or by me-

chanical breakage, the decomposition of the whole crystal proceeds very rapidly. A very characteristic feature, therefore, is the presence in soil of seemingly fresh individuals adjoining completely decomposed fragments. Intermediate stages are also to be found, but in small amount.

The end product of decomposition of hornblende and augite is clay material, usually dark red or, if manganese is present, violet-red in colour. In the case of hornblende the clay usually contains much alkali in colloidal combination. Phosphoric acid is sometimes set free in considerable amount by weathering of both groups, since they often contain quite numerous inclusions of apatite. Since the minerals are rich in iron the apatite is, however, firmly held and is but sparingly available for plants. The resulting clay is, of course, rich in calcium and magnesium.

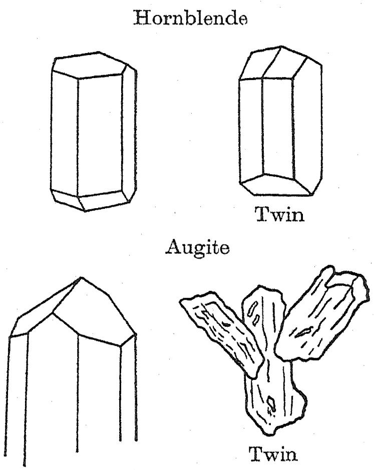


FIG. 6.—AMPHIBOLE AND PYROXENE.

In temperate climates, and still more in tropical climates, weathering of augite has as an intermediate stage the formation of so-called green earth, which sometimes lies in bands along outcrops of augite-bearing layers of rock. Where exposed, the green earth quickly turns to red owing to oxidation of ferrous oxide to ferric, and in consequence areas of this kind commonly show green summits and hillocks of which the weather sides and crests are red. Pyroxene and amphibole also often occur in

soil in well-shaped crystals, as shown in the accompanying illustration. The colour varies from dark brown or green to the deepest black. With a specific gravity of 3 to 3·5 all minerals of this group lie in Fraction A, which contains the heaviest particles and are accordingly very easily identifiable. Discrimination of the individual members of the group also presents no difficulty if the determination table is consulted. The most important single minerals of the group are the following:

(i) *The Hornblende Group*

Green or common hornblende, usually in the form of compact black-green grains.

Common brown hornblende, of a deep brown-black and often completely black colour, chiefly occurring in soils derived from plutonic rocks.

Basaltic hornblende exceptionally widely distributed, and very easily recognisable by the deep black and glossy surface of the broken material.

(ii) *The Pyroxene Group*

Rhombic pyroxene: enstatite and hypersthene, usually in thick columnar crystals, brown-black in colour. Hypersthene commonly shows metallic lustre.

Monoclinic pyroxene: diallage and augite, blackish brown to black; the latter is the commonest dark mineral of basic eruptive rocks.

Where amphiboles and pyroxenes occur in large amount in places where weathering is slow, as, for example, in big plains having a semi-arid, semi-humid climate, their dark colours naturally impart a dark colour to the soil. Although inspection with the naked eye is sufficient to reveal the particles which thus colour the soil, dark soils of this kind

are commonly called "humus sand soils", although they often contain no humus at all or, at most, scanty traces. In British territory these soils are classified as black cotton soils, from which they fundamentally differ in almost every respect.

(6*a*) *Carbonates*

It is hardly necessary to emphasise the practical importance of calcium minerals in the soil. To distinguish on mineralogical grounds between the calcium carbonates, calcite, aragonite and limestone, and their admixtures with magnesium carbonate, magnesian limestone and dolomite is a refinement of purely academic interest. All these carbonates are, however, very easily identified chemically, since the pure calcium carbonates effervesce strongly in the cold when treated with 10 per cent hydrochloric acid, whereas dolomite and magnesian limestone only slowly give off carbon dioxide when heated with the acid. Each separate particle is thus discriminated. Shell fragments are an important source of calcium in many kinds of soil, and are unmistakeable under the microscope.

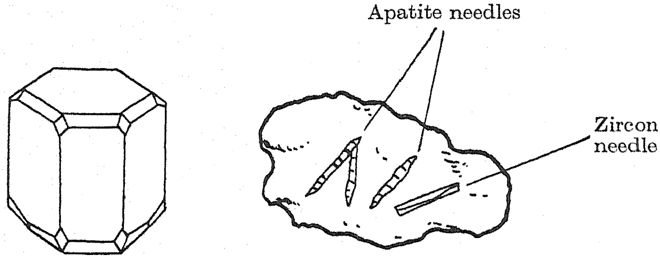
The carbonates of the soil are often secondary; for the most part they are constituents of concretions, and will be dealt with under that head.

(6*b*) *Gypsum*

The most prominent secondary calcium mineral is gypsum, which plays a part in the dry areas of the tropics and subtropics which is without parallel in temperate regions. Gypsum will also be considered with secondary soil minerals. As a primary mineral it is only found here and there, though sometimes in enormous masses forming dunes, as in Central America.

(7) *Phosphate-bearing Minerals*

"Apatite is the carrier of phosphoric acid in soil" (Ramann). It would be more correct to say that apatite is the source of soil phosphate. For when apatite is once set free in the soil it has so little resistance to weathering that one scarcely ever meets the free mineral in recognisable form. We have, however, already noted that tiny and often microscopic crystals of apatite are to be found as inclusions in the most varied minerals, such as dark volcanic glasses, quartz, felspars, hornblendes, biotites and so on. The accompanying



Single crystal (natural size)

Inclusions in a quartz grain (× 200)

FIG. 7.—APATITE.

figure shows the form of occurrence. The percentage content of these inclusions is for the most part small, but as apatite contains 41-42 per cent P_2O_5, quite small contents of apatite make such minerals notable sources of phosphoric acid, and they are the more valuable the more readily they break down and thereby expose their inclusions to decomposition.

In general, one may say that in a tropical climate a soil which contains one of the above-named apatite-bearing minerals (other than the highly stable quartz) is a soil amply provided with phosphoric acid. Whether that phosphoric acid is readily

available is a different question which will be fully discussed later.

It is an open question whether amorphous phosphates, in the true sense of the word, are to be found in soils which are chiefly mineral. In papyrus soils I have now and then been able to detect small aggregates of vivianite under conditions completely analogous to bog soils at home. The aggregates seemed, however, to be smaller and less frequent than is usual in the bog soils. Occurrence in such small quantity is without practical significance.

(8) *Primary Iron and Titanium Minerals*

Apart from iron pyrites, which is highly injurious, iron and titanium minerals have practically no

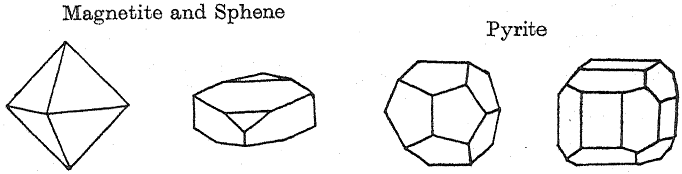


FIG. 8.—MAGNETITE, SPHENE AND PYRITE.

effect on the soil. They are mentioned here as being among the most conspicuous of soil minerals especially in regions of heavy tropical rain, where water running down stream beds or footpaths carries out a mechanical separation of minerals in respect to specific gravity. These heavy minerals accordingly often accumulate in noticeable amount under running water.

They are usually almost perfect in form, since they are very slowly affected by weathering and appear to the naked eye as small, rather angular black grains, while under the microscope their crystal form is immediately evident. The chief forms of the most important iron and titanium

minerals of the soil, magnetite and sphene, are shown in the accompanying figure. They are all more or less deep black in colour and nearly always have a marked lustre.

The only mineral of this group which is important in practical soil work is pyrites, iron sulphide which liberates sulphuric acid on weathering and is highly toxic. It is readily recognisable by virtue of its strong metallic lustre and yellow colour, together with its typical crystal forms, which are illustrated above. In case of doubt, liberation of sulphur dioxide on strong heating gives clear confirmation.

Soils which contain a notable quantity of pyrites, which is often shown up by a peculiar greenish yellow colouring of the soil, are completely unsuitable for any sort of cultivation.

In minute amount pyrites is fairly widely distributed and is not then injurious; it is in fact even useful as a source of sulphur, an indispensable constituent of plant food.

(9) *Secondary Minerals and the most important Small Concretions*

We shall later make a detailed study of certain more or less colloidal soil ingredients which are either residues of weathered rocks and minerals or have been formed comparatively recently within the soil. Such are: residual clays of the kaolin type derived from felspars; allophane-like alumino-silicates; mixed gels of alumina and silica, or of silica and iron hydroxides; and also iron silicates. All these have sorbtive properties and play an active and important part in the chemistry of the soil, and will be considered in that connection. We shall now mention only those secondary minerals which even the layman would pick out as discrete and well-characterised components of the soil mass,

and which, like the small concretions, are to some degree indicators of soil properties and are therefore of practical importance.

From this point of view gypsum is the most important mineral in all arid and semi-arid regions where a pronounced drought dominates for at least the major part of the year and produces an upward movement of water through the soil.

Gypsum occurs even in semi-humid parts of the tropics. It has a very distinctive appearance whether present in the form of fine needles or platelets or, as is not uncommonly the case, as a layer a few inches thick. It is thus present in soils of tall grass steppes and savannahs which are usually rich in humus and are always rather heavy, and is often very sharply restricted to the moist soil of small local depressions. The accompanying figure illustrates its most important crystal forms. The small crystals are sporadically distributed through the soil either singly or in small clusters, beginning at a depth of 8 or 12 inches from the surface. In regions of this kind the amount present is, as a rule, too small to have any direct harmful effect on crops. Occurrence of gypsum does, however, suggest the possibility of injury from high concentration of salts within the soil during the dry period and must accordingly be taken as a warning that thorough cultivation and, above all, efficient draining are indispensable in such areas. In arid and semi-arid parts of the tropics and subtropics the heavier soils nearly always contain gypsum. This is a consequence of increased upward movement of ground water and increased concentration of the soil solution during the greater part of the year.

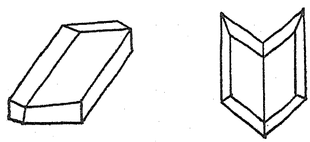


FIG. 9.—GYPSUM.

A further consequence of arid and semi-arid con-

ditions is the occurrence of gypsum in definite subsoil layers at depths which often vary between wide limits determined by rainfall, since the mineral is comparatively readily soluble. Whereas in semi-humid regions we find layers containing separate crystals of gypsum, in semi-arid conditions the layers form gypsum horizons and contain very large numbers of individual crystals. They then have a very harmful effect on plants. In the arid steppes of the tropics and subtropics a further stage occurs extensively: here the gypsum horizons form a solid floor which, as the upper layers of soil are carried away by wind, often comes to the surface and may form big exposed patches.

Where, under these climatic conditions, there is an upward movement of subsoil water, and where the parent rock of the soil itself contains layers of gypsum, the gypsum horizons develop into veritable seams of gypsum within the soil. These formations have a solid upper crust of gypsum lying 4 to 8 inches below the soil surface and extend downwards to depths which may exceed 3 yards, as has been observed in Asiatic deserts. Below the solid crust the formation has a quite characteristic foam-like or porous structure for which no explanation has yet been found.

These seams of gypsum are not, as a rule, disclosed by any surface indications other than a notable scantiness of vegetation. The surface soil in fact has the look of an excellent loess, and since abundant water is usually at hand in such places, has not uncommonly enticed the unwary to undertake cultivation. Such attempts are, of course, doomed to failure. Since gypsum seams of this kind are widely distributed in hot and dry regions which are of increasing interest to the agricultural pioneer by reason of their high fertility, it is highly advisable to carry out a most careful study of the soil

profile even when surface indications are very good, and so avoid the danger of making unpleasant discoveries at a later stage.

Calcium carbonate, formed within the soil and frequently mixed with silica, is of common occurrence in many soils of the tropics and subtropics. The formation of crusts and beds by separation of calcium carbonate will be discussed in detail later. Here we shall only deal with the small concretions which have not yet joined up to form these crusts or beds which are to be regarded as secondary rocks.

The best-known lime concretions are the cornstones or *Lösskindchen*, a name which refers to their common occurrence in all aeolian or loess soils. They are often of bizarre shape and, as a rule, begin to separate out around dead roots, which permit escape of carbon dioxide with resulting precipitation of calcium carbonate. Their size varies from a few millimetres to several centimetres.

They are usually formed by deposition of successive layers of calcium carbonate, and show by the inclusion of a certain amount of earthy matter that in the case of small dead roots deposition begins at the centre, so that the outermost shell is also the newest. Larger roots, however, leave larger spaces in the soil, as they decay, and deposition then begins at the outside and gradually fills the void.

These lime concretions, in spite of their name (*Lösskindchen*), are by no means limited to loess. They are also to be found in the black earths of the tropics and subtropics and wherever a soil rich in calcium is subjected to semi-arid or semi-humid conditions, which permit formation of the concretions. Like gypsum, calcium carbonate concretions occur in layers at depths which are greater with increasing permeability of the soil. The fact

that they are to be found in considerable amount on the surface of heavy soils, as in the grass plains of the tropics, does not mean that they were formed on the surface, but is a consequence of erosion by wind and, still more, of the automatic mixing of these heavy soils. The latter process consists in a continuous circulation of soil material within the depth to which the soil cracks on drying. This process is of great practical importance, but although it has been carefully studied in the Sudan it has not, to my knowledge, been described in any works on soil except perhaps for a mere mention. It will be considered in detail later.

With increasing heaviness of soil the calcium carbonate concretions, as a rule, decrease in size, and in clay soils dwindle to small round grains, which in dry climates usually have a black or dark-brown coating of manganese and iron hydroxides. They then strikingly resemble the so-called pea ore (oolitic limonite) or weathered garnets (almandines) and are very commonly mistaken for these, and not by laymen only. On closer inspection, however, their white kernels and lightness of weight readily distinguish them from pea ore or almandine. The distinction is of great practical importance, for like all calcium carbonate concretions the black dwarf forms indicate two things. In the first place, they indicate that one is dealing with a soil rich in calcium and one which is probably alkaline in reaction, a condition which is optimal for various tropical crops but which is exactly the reverse for others, and is indeed so unfavourable that an attempt to use such soils for these crops is necessarily futile. The second inference is that below the horizon containing calcium carbonate concretions the soil may be largely depleted of calcium, since its content of calcium has gone to the making of the concretions.

Even in the red earths of the tropics and sub-tropics small concretions of calcium carbonate occur in areas which are intermittently moist, and are there the forerunners of bed and crust formation. Their manner of formation and, to some degree, their composition also are, in my experience, so different from that of the concretions under discussion that they will be considered under the head of secondary rock formation.

The chief representatives of secondary minerals formed in soils of the hot zone are without doubt alumina and iron hydroxide. Here, according to the investigations of Fodor and Reifenberg, silicic acid very often plays the part of a protecting colloid except possibly in definitely hot and humid areas, where humus compounds have much the same function in this respect as they have in temperate climates.

Alumina occurs in crystalline form as hydrargillite in laterites and lateritic red earths. In laterites it is concentrated in or just below the surface, which is usually a hard bare crust. The mineral consists of small angular platelets often joined in clusters and white or yellow in colour. The clusters are usually separated one from another, but also commonly fill up crevices and cracks, forming a solid mass resembling calcareous sinter. In some places, as in India, the mineral occurs also as pisolite (pea stone) in appreciable amount. "One frequently sees the original felspars of a lateritic rock completely changed into a mass of small hydrargillite crystals" (Harrassowitsch).

Hydrargillite is the characteristic mineral of true laterite which is certainly fairly widely distributed in intermittently moist parts of the tropics, but is not by any means so common as was suggested when these formations were first described. Many of these reports were superficial and pretentious,

and were based merely on the look of the soil and primarily on its colour. One may now confidently assert that typical laterites are not so common as one was led to suppose in the confusion that attended and still attends that designation. This is fortunate, for true laterite is the *non plus ultra* of sterility, an inevitable consequence of the almost entire absence of plant foods, and often fails to support a single blade of grass even if no surface pan at once reveals its poverty. This is naturally not the case with the precursors of laterite among which are many red earths occurring in intermittently moist climates and in which no hydrargillite is to be found, at any rate within the depth of soil which is of practical interest to agriculture.

The colouring constituent of all red soils of the tropics and subtropics is iron hydroxide, occasionally and locally associated with notable amounts of manganese hydroxide. As to which hydroxide is present in particular cases and whether it should be described as brown iron ore, red iron ore or turgite are questions of scientific interest but have little practical importance. So also we shall not discuss whether the bright-red colour of many soils of the hot zone results from dehydration by heat and drought of newly formed compounds in the soil or whether, as recent researches seem to show, iron in colloidal combination with silicic acid sol is enhanced not only in mobility but also in colouring power. Two points only are of practical importance in this connection: (1) the exceptional ease of reduction exhibited by iron hydroxide; (2) its tendency to form aggregates and concretions.

Hydroxides of iron occur in soil sometimes as amorphous masses and sometimes as coatings on its mineral particles. Thus in dry subtropical climates red sands, *i.e.* ordinary sands coated with

iron hydroxide, cover wide stretches of desert. Red earths, in which coating of the soil grains and the presence of amorphous material contribute equally to the colour of the soil, occupy huge extents of the tropics and subtropics and vary in mechanical composition from sand to clay. One may say without qualification that a red colour characterises most soils of the hot regions of the globe. The red colour is, however, quite exceptionally fugitive, a circumstance to which, as far as I know, attention has not hitherto been drawn. This observation amply explains the banding of red with gray or black soils, such as is found in intermittently moist parts of the tropics and which is still looked upon as a puzzle. Thus where water containing a little organic matter lies even for a short time the bright red tint of tropical soils is quickly changed to gray or black as the iron oxides are reduced. The process is readily imitated in the laboratory by simple leaching with a weak sugar solution. This is why depressions in the red earth areas are almost always dark gray or black, and particularly so if the soil is heavy so that water penetrates with difficulty. Under these conditions big volumes of water, carrying bits of leaves and grass, stream in from all sides and stagnate in the hollow. The dark soils are thus simply reduced or leached red earths, and are not formations with an origin of their own. In suitable areas examples of this decoloration are readily observed under natural conditions. In local declivities of a red-earth district each heavy downfall of rain sets the water channels running and emptying themselves into the basin. Where the water laden with red mud overflows its banks, red tongues of the new deposit stretch far into the depression. Within a few weeks, however, no trace of them remains, and the uniform gray of the lowlying soil is again unbroken.

These low-lying soils contain as much if not more iron than the original red earths. Only the degree of oxidation is changed, and therewith the colour, which imparts to the declivities an appearance of being rich in humus whereas this is in fact present in very small amount.

Big expanses of heavy soil which do not receive so big a flow of water carrying organic debris, and areas or depressions where the soil is very permeable, naturally do not show this typical colour change. They remain red earths like the adjacent slopes.

The strongly marked tendency of iron hydroxide to form agglomerates, *i.e.* very stable soil grains, is of special importance. Its explanation will be given in detail under the head of soil-forming processes.

The stability of the grains is such that not only do they fail to decompose under natural conditions, but even in the laboratory they require drastic treatment. In mechanical analysis they are separated by their rather uniform particle size, and have been appropriately designated as "pseudosand" by Deuss. These pseudosand grains are rather like little sponges whose minute interstices are occupied by air or water. As a whole they are very resistant to attrition and change the physical character of heavy soils which consist of extremely fine material of colloidal size, so that they behave as light loams or even as sands. The change is very marked from a practical point of view and is confirmed by laboratory classification in respect to particle size unless strong reagents have been used to break down the concretions.

Soils rich in pseudosand—and to this class many if not most red earths belong—attract favourable attention by showing a number of practically important physical properties. Owing to the porosity

of their constituents their volume weight is comparatively low. They seem particularly light and, owing to the very stable structure of the soil grains, the soils are easy to work. They never show those plastic properties which give much trouble in other soils of the same mechanical composition by making cultivation impossible except at a certain moisture content. The pseudosand soils are permeable to water and air and form particularly good cultivable land, provided that they are well provisioned from a chemical point of view.

It is not chance but experience, based on crude but ancient agricultural schooling, that makes the native cultivator choose plots on red earth whenever he can, for in them he can most usefully employ his simple implements and has the best chance of obtaining a good yield. A similar preference for the red earth soils is often shown by planters. Unfortunately they sometimes go too far in this direction, for although quite poor washed-out or overcropped red earths show to a marked degree the granular structure which results from formation of pseudosand, this remains merely a physical feature of the soil and is no indication of its chemical properties.

Such a chemical indicator is found, however, in the second form in which iron oxide occurs in tropical soil. This is pea ore, a concretionary form. The concretions vary in size from solid lumps some centimetres thick to small grains which, as we have already noted, may easily be confused with weathered garnets or with manganese-coated concretions of calcium carbonate. The formation of beds will be considered later. In weathered allitic soils the concretions occur on or near the surface; in areas of siallitic weathering they lie in the lower layers of soil: but in either case they indicate the

age of the soil, and especially so when present in large amount.

Soils which are old enough to contain pea ore are usually more or less denuded of all bases and are therefore very indifferent media for cultivation. For this reason a thorough investigation is strongly advisable before any attempt at development. The soils are often notably rich in total phosphoric acid since the limonite grains sometimes contain a few per cent of phosphoric acid. As a rule, however, the phosphoric acid is so strongly combined with iron as to have no practical value. The occurrence of pea ore indicates a great mobility of iron in such soils, and this has a further consequence in that applications of soluble phosphate often have no effect since the acid is immediately fixed as insoluble iron phosphate. Such areas are best treated with raw phosphate, which in general gives a very good return in the red earths.

In this connection we must note a point which appears paradoxical at first sight. All red earths are more or less rich in iron, to which their colour is due. Percentages exceeding 10 or 20 per cent are not uncommon in old formations. This iron is present, however, chiefly in the colloidal state and not as ions. For this reason a very pronounced deficiency in iron is by no means rare in crops grown on red earth in spite of the fact that the high content of iron in the soil would make this seem unlikely. Unexpectedly good results have been obtained with the South Sea pine-apple crop, for example, by iron salt manuring when applied to the plants as a spray of dilute solution. Occasional expressions of opinion to the effect that chlorotic symptoms on red-earth crops are traceable to lack of iron and that manuring with iron deserves practical consideration, are not therefore untenable, as has frequently been suggested, but are, on the

contrary, well founded, provided, of course, that one does not attach too much importance to iron nor attributes every nutritional disorder of one's crops to deficiency of iron in the soil.

The last group of newly formed minerals, which is of theoretical and practical importance in soils of the tropics and subtropics, consists of the soluble salts of magnesium and the alkalies which separate out in crystalline form either at the soil surface or in certain soil horizons. Nitrates belong to this group as a sub-class of local occurrence.

Alkali carbonates lead to the formation of "black alkali" soils and give a *p*H value of over 8·9 for the soil reaction. Where the soluble salts contain no alkali carbonates they are known as "white alkali" and are comparatively harmless if the soil permits drainage and if ample irrigation water is to hand. Even soils that are covered by a definite crust of salt during the dry period can be converted into good cultivable land by simple leaching and within a relatively short time. Salt contents of 0·1 to 0·15 per cent are sufficient to show efflorescence at the soil surface during the dry period but are relatively harmless in respect to the crops cultivated in arid districts of that kind. The lethal concentration of soluble salts for all crop plants lies at about 0·3 per cent, this figure being an average from which there may be big variations corresponding to differences in composition of the salts.

Care is needed in the cultivation of soils which show a tendency towards accumulation of salts and is specially necessary where irrigation is practised. The problems arising out of such conditions will be considered later.

The same holds for the "black alkali" soils which contain carbonates and constitute one of the most formidable problems of soil work in arid climates. These black alkali soils sometimes extend over wide

areas but are more usually rather small and well defined. They are recognisable by their dark colour, which is due in part to their higher moisture content, which results from the hygroscopic nature of the salts, and in part also to the presence of dark organic compounds. Areas of this kind often have the appearance of grease spots in contrast to the rest of the district. As a rule they are completely bare of vegetation owing to the strong alkaline reaction of the soil.

Much the same is true of soils that are highly impregnated with alkali or calcium nitrates. They occur in the tropics and subtropics more commonly than was supposed in view of the fact that accumulation of nitrate requires conditions which are not likely to be satisfied in many places. Recent study of saline efflorescences in semi- and wholly dry districts has, however, produced many surprises in this regard, and their number will probably increase with the increased attention now paid to these formations.

Except for known beds, such as those in Chile, deposits sufficiently rich to be worth quarrying have not been found. For supplying local requirements of nitrogenous manures some of the small deposits are not to be despised and it is well worth while to examine salt incrustations from this point of view. Small nitrate deposits are quite numerous in Central Africa and subtropical Asia and must be present also in the hot parts of America and Australia. They have a very typical feature in the instability of their salt efflorescence. Whereas ordinary surface incrustations require a fair amount of water before dissolving, these disappear with the lightest rain and return as rapidly on drying out. This is due to the very high solubility of nitrate.

Even a moderately high content of nitrate is enough to make land useless for cultivation.

II. THE MOST IMPORTANT SOIL-FORMING ROCKS

Whereas mineralogical examination and assessment of soil within a small area gives an idea of its lasting power and its probable chemical properties, sound knowledge of the parent rock is a valuable practical guide as to what kind of soil profile is likely to occur in the district, at any rate, in the case of soils formed *in situ*. It is of course clear that little can be gained from study of the parent rock in the case of transported soils, which may perhaps have been moved long distances by wind or water and have been influenced by a variety of factors during deposition. The profiles of such soils bear not the least relation to their parent rock, and even in composition are only distantly related to it.

Soil is formed *in situ* by the disintegration and chemical transformation of rock under the influence of weathering factors, of which, after temperature, the most important are air or oxygen and water, which is to be regarded as a fairly dilute solution of certain substances. The success of an attack is greater as resistance is less and as the area under attack is greater. In the case of rock attacked by weathering, disintegration and decomposition proceed most rapidly and produce the deepest soils where the minerals of the rock and its cementing materials are (1) least resistant to the attack of water and air under the high temperatures of the tropics and subtropics, and (2) where the area of rock exposed to attack is most extensive. As regards the first point it should be noted that abrupt variations of temperature such as occur in the subtropics increase the rate of weathering. The solubility of rock constituents is, strictly considered, extremely small. Only carbonates show an appreciable solubility, which is made evident in calcareous and

dolomitic districts by the rock becoming furrowed and pitted and giving rise to what is known on the Continent as *Karrenfelder* and *Verkarstung* (Karst land). However, constant dripping wears away the stone and no mineral is absolutely insoluble.

A factor of much greater importance in soil formation than solubility in the strict sense of the word is the readiness with which minerals and cementing substances break down when attacked by air or water. In air oxygen is the active substance, and in water a number of dissolved substances including oxides of nitrogen, carbon dioxide, various salts and also organic substances, some of which are acidic. The oxides of nitrogen are strongly acidic, and the water thus contains not only cations like the hydrogen ion, which to some extent displace cations from combination in the minerals, but also the necessary anions which for a time keep the freed bases in solution.

In general, processes of this kind occur the more readily as the attacked molecule is more complex. Thus, alumino-silicates of high molecular weight break down very easily, especially, as was noted above, when they contain the lower oxides of iron or manganese which react with oxygen with evolution of heat, that is, with loss of energy.

Other things being equal, dark rocks, that is, rocks coloured by dark ferrous minerals, disintegrate under weathering more rapidly than light-coloured rocks. The expression "other things being equal" is used deliberately, for the arrangement of rocks in order of resistance to weathering may be completely masked by such differences as the area exposed to weathering and, inevitably associated with this, differences in the time during which water acts on the rock components. A smooth surface of rock withstands weathering for thousands of years, since water simply runs off it unless the surface is

absolutely horizontal, a condition which never occurs in Nature over any wide area. No matter how heavily laden with active substances the water may be, it has practically no time in which to act, while the oxygen of the air reacts but slowly with the dry mineral.

The condition is quite different when the rock surface contains cracks and crevices into which water and air penetrate. The moisture is then held for very long periods and air has access to a surface which is already much increased and which rapidly extends still further as weathering proceeds, since the walls and minute crevices of the fissures are not uniformly attacked but are roughened so that within a short time the naked eye can detect appreciable unevenness of surface. In this way weathering begins at cracks and fissures and eats like cancer into the rock mass.

Whether the faults and cracks were originally present in the rock or whether they easily appear depends entirely on the structure of the rock. Internal strains within the rock are relieved in this way and so play an important part.

When the rock consists either of loose grains or of grains which are but feebly cemented and when the cementing substance is readily soluble, weathering begins on the surface and rapidly goes to great depths. Examples of such rocks are volcanic ashes and sands and most soft tuffs. Soils of great thickness result from this, and in them very close attention is needed in order to detect the transition from soil to mother rock, and in some cases the discrimination can hardly be made.

Where cementation of the soil grains is harder, as in compact tuffs and many sedimentary rocks, and where the cementing materials are neither soluble nor reactive, weathering agencies have little effect even where other conditions are favourable. Shallow

soils are then formed, deepening only in occasional pockets over the bigger fissures in the rock. As a rule the superficial appearance of such soils gives no clue to their worthlessness except sometimes by patches which are bare of natural vegetation. It is urgently in the planter's interest to examine with care the subsoil in districts where such rocks are found. Cases in which neglect of this precaution has led to heavy agricultural loss are unhappily quite common in spite of the fact that no one is in doubt as to the need for definite information about the subsoil of new land. The theory is admitted, but unfortunately there is sometimes in the drowsy climate of the tropics an unbelievably wide gap between theory and practice.

With regard to the production of deep soils, all granular rocks may be considered relatively favourable. The individual crystals should be large enough to be easily picked out by the naked eye. It is particularly advantageous when the rock consists not of one but of several minerals, since these all have different coefficients of expansion. Even small variations of temperature set up strains which are released by cracks and fissures, and these in turn set in action other stresses already present in the rock. In this manner granular rocks weather *in situ* under semi-humid tropical and subtropical conditions to considerable depths, which are as a rule ample for agricultural needs. In humid climates soils thus formed are so deep that their thickness far exceeds practical requirements. In dry climates the depth of weathering and consequently depth of soil leave much to be desired even with granular rocks, and caution should therefore be used.

Compact rocks which either consist of minute and closely packed crystals or are cemented by a resistant material form cracks and fissures only to a very limited extent. This is the case, for example,

with rocks in which the cementing material is lava and consists of homogeneous glasses. Since the exposed surface is small, such rocks are very resistant to weathering even when their constituents are themselves comparatively vulnerable in this respect, as are, for example, dark volcanic glasses. Soils formed *in situ* from such rocks reach an ample depth only under a humid tropical climate; elsewhere, they are dangerously shallow as a rule.

In all rocks large cracks and fissures arise from rupture at surfaces of jointing in volcanic rocks and between the layers of sedimentary rocks. Such cracks promote weathering in accordance with their position and shape, which determine their ability to retain water. Least favourable is the spheroidal weathering commonly seen in basalts and diabases, for although the rock surface is certainly increased it remains minimal. Most favourable are lamination or jointing, which give scope to the continued action of water and air.

The physical nature and mechanical composition of soils derived from particular rocks depend on the ratio of the resistant minerals to the non-resistant constituents.

Table II, in the appendix, presents a survey of most important volcanic rocks in respect to their composition and their behaviour on weathering.

Volcanic ashes, sands and tuffs have been mentioned above. The kind of soil which develops from them depends entirely on the character of the glasses and minerals which compose them and on the fineness of the volcanic dust. For every volcano this is a function of distance from the active crater, since the coarser particles naturally settle more rapidly than the finer ones. Thus sands predominate near the volcano and the particles become smaller with increasing distance. The very finest particles of dust are carried to great heights and may remain

suspended in the air for years. In the neighbourhood of an active volcano one usually finds that the soils are arranged in concentric zones with light or sandy soil nearest to the centre.

Whereas volcanic rocks, despite their variety, show a great regularity in composition, which is determined by the way in which the magma solidifies and by the order in which the various minerals separate out, there is no such regularity in rocks which are strictly sedimentary. These are all deposited as loose sediments of material derived from volcanic rock by disintegration and decomposition. They are, for the most part, fossil soils with variations subsequently imposed by cementation leading to a greater or less degree of hardness. The cementing material may be formed by the finest particles of the deposited material, modified perhaps by some chemical change, but it is often introduced in solution from some outside source and then gives the sediment a character which was not present in the original deposit.

The most important cementing substances to be found in sedimentary rocks are the following:

(1) *Clay materials*, which as a rule originate from the deposited material itself.—Sediments with clay cementation do not as a rule show much resistance to weathering, and therefore form fairly deep soils. This is particularly noticeable in the humid tropics, but is also quite general in the tropics and subtropics. What other properties the soil has depends, of course, on the kind of material forming the deposit.

(2) *Ferruginous Clay Cements.*—These cements are widely distributed in all classes of sedimentary rock. They may be derived from the sedimentary material itself or may be brought in from outside as a soluble iron salt. Such rocks usually show con-

siderably greater resistance to weathering than do those in which cementation is by clay alone.

(3) *Iron Cement.*—This consists of brown iron ore and is comparatively rare in its pure form. Where it occurs the sediments are as a rule highly resistant to weathering and the soils formed from them *in situ* are exceptionally shallow.

(4) *Lime Cement.*—This is formed either from the deposited minerals or is carried in solution from outside sources. Sediments with lime cementation are often very tough and weather very little, so that only shallow soils are formed from them. On the other hand, sediments with marly cementation in which lime is associated with clay break up as a rule still more easily than do those with pure clay cementation, and are accordingly comparatively speedy builders of soil.

The remaining varieties of sedimentary rocks are cemented with silica or glauconite and are practically worthless as being too resistant to form soils.

(5) *Siliceous Cement.*—This rapidly forms opal between the particles and builds up broken fragments of quartz into a solid mass.

(6) *Glauconitic Cement.*—Sedimentary rocks adjacent to existing or former sea coasts are often cemented by glauconite and indeed in many places largely consist of this substance. Such rocks are of great practical importance. Glauconite is a hydrated silicate of potassium associated with iron oxide and clay, and may contain as much as 15 per cent potassium, and usually contains at least 10-12 per cent. It forms small green grains in many sedimentary rocks, especially in green sandstone, and in the form of green mud or green sand is still widely distributed, particularly in the so-called hemipelagic deposits between the shore and the deep sea of warm coasts which have few rivers. It shows

a special taste for forming inside the skeletons of marine foraminifera. The chemistry of the formation of this curious mineral is not yet understood.

The potassium content of glauconite is equal to that of many crude potassium salts, and attempts were naturally made to use this mineral as a potassium manure in temperate climates. Trials were made on a wide scale in America, but gave very indifferent results. The combination of the potassium with the iron-silicic acid component is apparently too firm to permit rapid enough solution to have a manurial effect on plants. In the tropics large dressings of glauconite cannot replace potassic fertilisers, but none the less they serve as a valuable soil improver.

As a whole, sedimentary rocks are stratified formations which are distinguished as being of mechanical, chemical or organic origin.

Mechanical sediments, often occurring as beds, have a granular structure in which the grain size shows the widest variations from boulders to the finest dust. If the material has been transported only a short distance the grains are angular. Unsolidified and uncemented, the material is angular gravel or scree; cemented, the jagged fragments constitute breccia. Where the material has been rounded by transport one speaks of gravels, sands and clays if there is no cementation, or of conglomerates and graywacke in the contrary case, the latter term indicating a high content of felspar. The less coarse cemented material forms sandstones which are further characterised as above in relation to the nature of the cementing material. Clays are converted by cementation into clayslate and finally into phyllite.

That the sedimentary rocks vary in content of plant foods according to their manner of formation

is self-evident. F. Heide gives the following figures as the mean of a large number of analyses:

	Na_2O %	K_2O %	CaO %	MgO %	P_2O_5 %
Sandstones .	0·1-0·24	Tr.-4·5	Tr.-0·6	Tr.-1·3	Tr.-0·02
Claystones .	Tr.-2·0	Tr.-3·2	Tr.-2·0	Tr.-3·3	Tr.-0·06

It is obvious that all mechanical sediments with very few exceptions can only form very poor soils, and great care is therefore needed in the selection of such areas.

Of the chemical sediments only limestones and dolomites are of importance as soil formers, since sulphates and chlorides never produce structures suitable for plant growth or capable of being called soils. These calcium and calcium magnesium carbonates are extremely widely distributed. Apart from calcium and perhaps magnesium they usually contain but little plant food. The content of phosphoric acid ranges from nothing up to 1·7 per cent, varying so widely that it has to be determined in each particular case, while potassium and sodium are present only in minute amount. Under the influence of hot climate the red or red-brown terra rossa is almost invariably formed from these rocks, and one must therefore be ready to face the possibility of pronounced deficiency of potassium except where the terra rossa has collected additional building material carried either by wind or water.

Sediments of organic origin will be considered in detail later in so far as they are of interest to pedology.

When sedimentary rocks come under the influence of high temperature and pressure they are changed to metamorphic rocks, and the same process sometimes takes place in unstratified rocks as well. The metamorphic rocks usually have a slaty structure, and in texture are usually granular, sometimes compact and occasionally massive. Their most important representatives are:

(1) *Gneiss* is distinguished as felspar gneiss, mica gneiss, hornblende gneiss, etc., with regard to its dominating mineral, and its value as a soil-former varies accordingly. Biotite and hornblende gneiss yield the richest soils, which are usually more or less red in colour.

(2) *Eclogite* and *amphibolite*: usually dark rocks in which basic minerals predominate and which weather fairly easily to strongly coloured and usually fairly rich soils.

(3) *Magnesium silicate schists*, to which belong chlorite, talc and serpentine schist, and further olivine, hornblende and augite schists. Of these only the two last groups form rich soils which are usually red, whereas the other schists usually form poor soils.

(4) *Quartzite rock* is the product of sandstone consisting mainly of quartz and produces very poor sandy soils, which are mostly light in colour.

(5) *Calcium Silicate Schists.*—Calcium silicate rocks of very dense structure and calcium phyllite. Owing to the high variation in mineral composition of these rocks it is not possible to make any generalisation as to soils derived from them except that, owing to the slowness with which these rocks undergo weathering, soils formed *in situ* are shallow as a rule.

(6) *Marble.*—This is practically pure calcium carbonate, and may be considered as equivalent to pure limestone (see above), but is for the most part even poorer in plant foods.

III. SECONDARY FORMATION OF ROCK IN SOIL

Whereas secondary formation of rock in soil is rare in temperate climates and, except for incipient pan formation, is of little practical interest, in warm regions of the earth it is both common and

important. For when the rock lies at the soil surface it excludes all cultivation except after operations of prohibitive cost. When the rock lies deeper in the soil it may restrict development of plant roots by forming a barrier between the surface and the subsoil. When, as is unfortunately still commonly the case, investigation of the subsoil has been neglected the presence of this obstacle is first shown by the death or stunted growth of the crop, that is, when it is too late to remedy the original mistake. These formations are accordingly a menace to deep-rooting perennial crops, and the meagre yield or failure of many agricultural undertakings in the tropics and subtropics is due to neglecting the possibility of their occurrence.

The least widely distributed of all the secondary rock formations are those of which the chief constituent is silicic acid, which separates out either at the soil surface or at a certain layer in the soil profile and so binds the soil grains as to form a solid floor or a more or less impermeable layer within the soil. In English-speaking districts these formations are called hard pans irrespective of their composition. The formation of such silicate layers, beds or crusts is limited to hot and dry districts. Only there has the soil a sufficiently alkaline reaction to make silicic acid mobile enough for the formation of beds or crusts. Weakly siliceous layers of varying depth are to be found in all dry subtropical areas. They are particularly well known in Asia Minor. In the central table-land of Australia they extend from the surface to the huge depth of five yards or more, and are responsible for the almost complete absence of vegetation from the higher areas, where, alternating with iron crusts, they extend for thousands of square miles. Vegetation exists only in cracks and crevices where a few drought-resisting types manage to cling to life.

How far the occurrence of hard pan in the humid and semi-humid tropics is also due to enhanced mobility of silicic acid is not yet known. These hard pans are found in districts containing basic rocks, as in Java, where the so-called "haarde Tjadas" provide an example of this formation.

Much more common are the new formations in which the chief constituent or cement is iron hydroxide, chiefly in the form of brown iron ore.

In regions of intermittently moist tropical climate, iron rises to the surface during the dry period and there forms a hard solid crust of laterite which may extend without a break over considerable areas. In these the brown iron ore cakes to a cindery mass hard as rock and penetrated by twisted tubes of a lighter but no less compact material, while the interstices contain whitish or yellowish aluminium hydroxide and hydrargillite, the characteristic mineral of laterite. Occasionally residual kaolin and unweathered quartz are also found.

Bog iron ore occurs in many forms, of which one presents almost exactly the external appearance here described and has misled even geologists into confusing it with lateritic crust. It has a wide distribution in the moist tropics and subtropics, and in some places, such as Mozambique, although subsequently covered by a shallow layer of soil, it makes successful cultivation impossible over wide areas. On closer examination the complete absence of hydrargillite and of alumina gels immediately shows that this is no laterite crust but a formation of quite a different kind.

As in temperate climates, this iron mineral is formed where water containing iron comes in contact with air, and the process is much accelerated by acid humus. The fringes of temporary or permanent swamps and lakes, as for example Lake Victoria in East Africa, provide conditions which favour the

formation of thick beds of bog ore. Where bog ore is now found below the soil surface one may usually infer that the area was formerly swampy. Iron bacteria probably play a large part in the formation of bog iron ore.

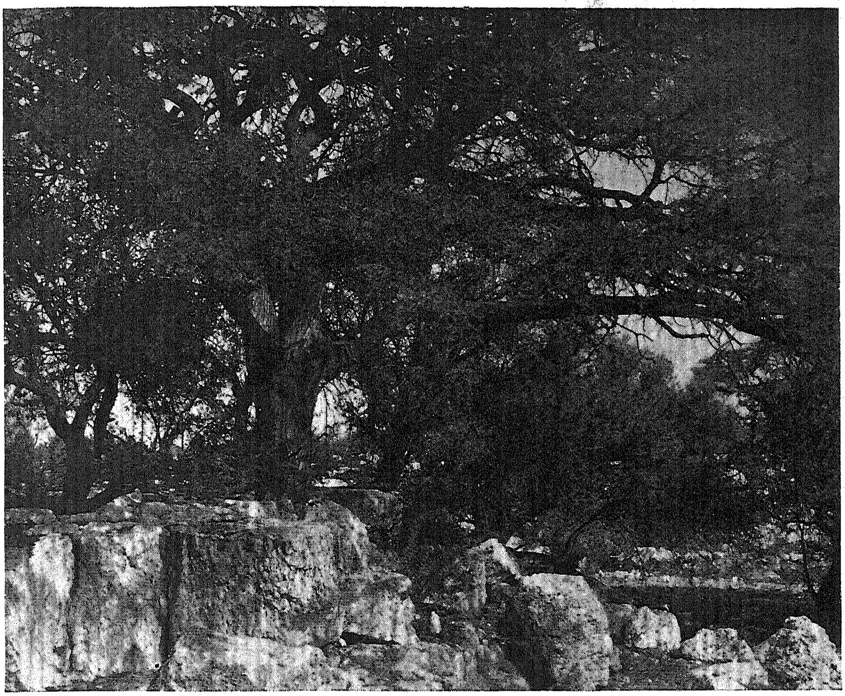
The third type of occurrence of deposits of iron hydroxide in soils is as a sort of iron ortstein, which occurs throughout the moist tropics and subtropics in the same form as the ordinary ortstein of the temperate regions. In the tropical ortstein, the iron and not the humus predominates, although the latter, of course, is not absent. This ferruginous ortstein is connected with the bog ore by a series of intermediate stages. It occurs principally in the light sandy soils of the tropical forest peats and in many primaeval forests. It is not restricted to great elevations, but may even occur at sea level, where the humus has a very strongly acid reaction. The iron ortstein of the tropics, like the humus ortstein of the temperate regions, is always covered by a layer of bleached sand, which is often of considerable depth and is, in turn, overlain by a layer of acid humus. In heavy soils these formations are but poorly developed and may not go farther than changing the soil colour. The distribution of bleached sand and iron ortstein in the moist tropics is not yet even roughly ascertained. They are probably almost as widely distributed in the forest belts, and especially in the extensive swampy areas of the tropics, as is ortstein in temperate climates. A striking feature is that certain tropical grasses, such as *alang-alang* (*imperata cylindrica*), a weed dreaded throughout the Indies, vigorously promote ortstein formation in acid soils. In such places one may find under almost every tuft of *alang-alang* a miniature ortstein formation from which no typical characteristic is lacking. In contrast to temperate climates the chief cementing

and colouring constituent of these formations is always iron.

In the dry tropics and notably in the subtropics lime displaces iron as a builder of secondary rock. Wherever rocks rich in calcium—and this includes nearly all basic and a good part of the acidic volcanic rocks in addition to sediments rich in calcium—are subjected to alternating wetting and drying thick lime crusts are formed at the rock surface. These are often many yards thick and stretch as beds or pans into depressions which they sometimes completely encircle. Up to the present the biggest lime pans are found in South Africa, where their formation probably dates back to very ancient times. To what extent lime-bearing springs are, or once were, concerned in these formations, and what was the precise manner of development, must be determined by detailed investigation in each particular case. It is to be noted that these pans of secondary limestone are by no means absent in the dry tropics but often fringe and almost fill depressions in the steppes.

There are two points of practical importance in respect to these lime pans. Even to-day many of them carry water at some depth and often in considerable amount. For the most part they are recognised as watering-places by the native population. Another characteristic is that almost all form a peculiar kind of soil which cannot be mistaken for that derived from any other rock. Owing to its low content of iron, soil formed from secondary limestone is whitish gray. When dry it is an impalpable fine dust which makes very heavy walking, and when wet it becomes a slippery mud which, if of any depth, completely holds up traffic. The depth of soil is as a rule small, as may often be inferred from the absence of trees. Only where deep cracks occur does one find acacia or mimosa with roots

PLATE I



Lime Pan beside Watercourse (South Africa)
(Note growth of trees in cracks of the lime crust)

extending to the level of ground water. Plate I gives an illustration of a typical limestone pan. The gray dust soils have little or no value for cultivation.

Secondary limestone formation in which soil material is cemented by the introduction of a solution containing calcium is not uncommon. The solution may either sink into the soil from the upper layers as happens in moist climates, or rise from below where the climate is dry. The depth of these hard pans is accordingly dependent on local conditions. These formations are often so hard that they can be broken up only by explosives, an operation which under certain conditions of agriculture may give an economic return.

In recent volcanic and particularly in ash soils there occur in moist climates secondary formations in which the cementing material is clay or a mixture of clay and marl. These accompany the secondary formations already described. In them cementation of the lower layers of soil is carried out, at any rate in part, by fine material which is washed down from the upper layers. These are the "Zachte Padas" of the East Indian planter, although this expression sometimes also denotes either the decomposition zone of the adjacent rock or, in districts where volcanic activity is high, weathered material derived from layers of bombs and lapilli.

In hot climates attention to subsoil conditions is much more urgently advisable than in temperate climates.

CHAPTER III

FORMS OF VEGETATION IN THE TROPICS AND SUBTROPICS AS SOURCES OF ORGANIC SUBSTANCES IN THE SOIL

IF the agriculturalist who for the first time enters the torrid zones be asked what is the most striking feature of tropical soils as compared with those of a temperate climate, he will as a rule be ready with an immediate reply. Nature has lost at a blow the brown tints shading into yellow and black with which she is endowed by soils at home. Light gray, dull yellow gray, ranging from the lightest to the darkest shades, deep black almost devoid of any brownish tinge and dazzling white alternate with gleaming red which becomes richer as one nears the Equator, and often changes into green and violet tints below ground level. Only exceptionally does one see the familiar soil colours which are produced by humus under temperate conditions. For this reason the request for a particularly striking difference between tropical and temperate soils nearly always receives the answer: tropical and subtropical soils seem to be very low in humus. This superficial impression, of which the meaning is quite clear, has been crystallised in many textbooks on soil in much more definite terms: tropical soils are low in humus. It was a short step to the inference that in practice it is not necessary to bother about the humus content of tropical soils if none is present

in any case. It is this maxim that has repeatedly involved the whole of tropical and subtropical agriculture in heavy and fruitless expenditure, while, on the contrary, appreciation of its falseness accompanied by appropriate methods of soil management has proved to be the turning-point towards new prosperity in the case of whole agricultural areas.

The question as to what one means by "humus" is easily answered. Humus, in the general sense, means all soil organic matter which has lost its original form as plant or animal remains and which has been changed into a more or less homogeneous, predominantly colloidal mixture of secondary substances. As to what these colloidal substances are individually is probably as far from a satisfactory solution to-day as it ever was. It is a wholesome sign of the times that the International Society of Soil Science has established a special commission for the study of humus, and we may expect that this very complicated field will be thoroughly covered by these investigations. At the moment there is no information on this matter in spite of the fact that it is of as great practical interest in the tropics as in the temperate parts of the earth.

Agreement has in fact been reached only on two aspects of the humus problem. Undoubted importance is attached to humus as the carrier of most plant foods, that is, as a kind of universal soil substance which effectively supplements the stock of plant food held in inorganic combination because part of the plant food combined with humus is readily available. A more important function, however, is the provision of nitrogen and of carbon dioxide and general improvement in the physical condition of the soil. Opinion is further agreed that the transformation of plant and animal remains into

humus is largely, if not mainly, brought about by the activity of lower organisms, so that in the case of humus we are dealing not with a secondary but with a tertiary product. This practically concludes the positive knowledge and unanimity of soil workers in respect to humus.

European scientists, of whom Sven Oden and Hissink may be specially mentioned, are inclined to maintain that in humus we are dealing with well-defined chemical substances of a special kind, and in short with special humus substances which behave to some extent as true acids and react accordingly and, in particular, form salts. American workers, on the other hand, take a different view. Shorey, Waksman and others have isolated so many simple well-defined chemical substances from soil humus that they and their school regard the resolution of the humus mixture into its simplest chemical components as a problem to be taken in the stride of their present enquiries. From this point of view there are no special humic substances but simply a mixture of many substances which does not fluctuate very widely in its composition. What appear to be peculiar properties of humus have led to the production of formulae for various humic bodies, but are no more than the properties of this group of mixtures. The fact that "humic substances" have, in apparent opposition to this view, certain constant properties and reactions such as a carbon content of about 58 per cent and a carbon-nitrogen ratio ranging from 8 : 1 to 12 : 1 is explained in that the mixture is made of so many components that the absence of some or the entry of new members cannot greatly affect the mixture as a whole.

The two views seem irreconcilable; the divergence, however, is not, as Sven Oden has remarked, as wide as it appears. Admittedly a large number of

known simple chemical substances must be present in humus, since these are already present in the starting material or are readily formed from it. The isolation from humus of resins, fats, organic acids and so forth is not a matter for surprise. One may equally admit that if there were a special humus molecule it would certainly be of great size and, when treated with reagents, would either split off simple substances of the most varied kind or else entirely break up into its simplest components. Proof that true humus in the chemical sense does not exist is not provided by the mere determination of simple products in the soil. Here also some middle view is probably correct.

It is still an open question how nitrogen is combined in soil, and how this combined nitrogen may be made available for plants to a greater extent than at present. The greater part is apparently present as protein, but by no means the whole. This is a question of outstanding practical interest, for even soils which are low in humus carry some tons per acre of more or less unavailable nitrogen. We know equally little about the phosphoric acid content of humus substances. This is sometimes quite considerable and very commonly constitutes the major part of the total phosphoric acid in soil. It is only in respect to the behaviour of the bases in humus that much light has been shed, and this we owe to the work of Hissink. On the whole, therefore, elucidation of the humus problem may be regarded as a very attractive field for research. This is true for the temperate zones where humus has been under investigation for over a century. Of humus forms in the tropics we know hardly anything except that they exist and are of great importance in cultivation.

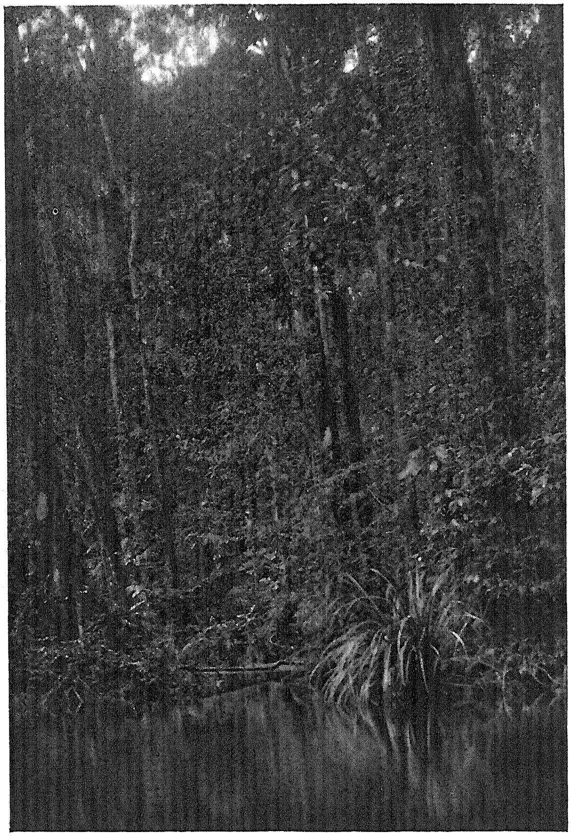
Humus substances, to which the familiar ideas of the temperate regions are applicable, are found

chiefly in the very wet uplands. Here they vary, exactly as in the temperate regions, from the so-called "mild humus", saturated with bases especially lime, to the "acid humus" which leads, just as in the temperate regions, to the formation of ortstein generally, through the greater activity of the iron, to a ferruginous ortstein, but occasionally to a true humus ortstein.

Externally the peat soils of the tropics and sub-tropics are very similar to those of temperate climates, and, contrary to the opinion expressed in many recent textbooks, they are in fact widely distributed and take in considerable stretches of land. If we exclude the sphagnum peats (*Hochmoor*), which occur only at great heights and thus fall climatically into temperate zones, we find that the similarity shown by other swamp soils is merely superficial, for their composition is very different from that of the swamps of temperate regions.

The mightiest accumulations of organic matter occur in the tropics, where a sort of fen (*Flachmoor*) follows the silting up of standing water, slowly running streams and poorly watered deltas. In the streams of tropical Africa, which are either rich in calcium and other plant food or which, by continuous addition of water and evaporation, are enriched in salts without becoming actually saline, papyrus is the most important contributor of organic matter and rapidly clogs up the river-bed. Enormous beds of papyrus, often inextricably enmeshed by climbing plants, girdle the flat shores of African lakes and slowly but surely encroach on the free water surface. They narrow down the beds of the great African rivers, such as the Congo, Niger and Zambezi, and in the upper reaches of the Nile below Lake Victoria form the huge "Sudd" area lying within the Sudan. The Sudd covers thousands of square miles where the Bahr-el-Jebel and the

PLATE II



Forest Swamp (Waldmoor) on the East Coast of Sumatra
(Note epiphytes and poor development of the tree trunks)

Bahr-el-Ghazal meet, forming a mass which even at the beginning of the present century proved a serious obstacle to river steamers. The depth of swamp soil formed by the matted residues of the papyrus clumps often exceeds ten yards. The content of solid matter is very low. On drying the mass shrinks to a fraction of its volume and is light as a feather. When the papyrus swamp is drained and dried, however, it forms cultivable soil comparable in quality with the calcareous fens (*Flachmoor*) of temperate climates.

In the American tropics and subtropics papyrus gives place to bulrushes, and in Asia to reeds, neither of which approach the development of papyrus. The reed *Arundo* is to be found all over the world, forming swamps and silting up water channels. In this respect it is an important factor in some localities, although it does not, of course, compete with papyrus. However, the swamp formations here described are limited to certain places, since the conditions requisite for their development are not generally satisfied even in districts of high rainfall. Forest peats have a much wider distribution in the tropics and subtropics, both in regions of heavy rainfall and also where the climate is intermittently moist. These forest peats (*Waldmoore*) extend to the sea coast as in Sumatra and Borneo, and are to be regarded as the end product of forest swamps (*Waldsümpfen*) which readily form in badly drained depressions. (*See* Plate II.)

As such they can be formed from water which does not carry much debris, if excess water is present sufficiently long to retard the decomposition of the dead plant matter so that a gradual accumulation of humified material can take place. This usually occurs comparatively slowly, for not every tree or other plant will stand up to the long-

continued waterlogging. The composition of such forest peats is usually limited to comparatively few varieties, which as a rule do not grow particularly tall and are not luxuriant, producing relatively little organic matter each year. Short trees, sometimes with broad stilt-like roots, mixed with palms, are commonly seen, and often rubbishy scrub which contrasts strongly with the vigorous vegetation lying beyond the waterlogged area. As would be expected, these forest peats carry certain characteristic plants in various parts of the torrid zone and have received distinguishing names from the natives. Further study of this would, however, lead us too far. Throughout the world these tropical and subtropical peats have one feature in common in that the surface layer of humus is usually shallow. Only here and there does it exceed a yard, where depressions of the subsoil have permitted an exceptional accumulation of organic matter. Further, according to all observations now available, the humus formations are without exception strongly acid, a consequence of the fact that the water they receive is mostly rain-water and accordingly is of low salt content. In accordance with this the subsoil of such peats, if permeable, shows a thick layer of bleached sand with iron ortstein or, less frequently, with humus ortstein. Where the soil is heavier it is usually discoloured to a considerable depth and is frequently impregnated with reducing substances.

These forest peats reach an enormous development in the region of the Upper Congo and Lualaba, in the East Indies, in the north of South America (particularly by the Amazon and Orinoco rivers), as well as in Central America. According to present reports quite a considerable part of New Guinea is entirely composed of forest peat.

Owing to lack of plant foods in the thin peaty

layer and to the heavy leaching of the subsoil, shallow formations of this kind form very inferior culture media in spite of the seductive appearance of the humus layer. They demand thorough drainage, which is not always possible, and soon need heavy applications of artificial manures to supplement the plant foods. Deep swamp soils, on the other hand, are by no means rare near the coast and are to be judged in the tropics by considerations which differ from those applicable in temperate climates. They are certainly low in mineral matter and are as a rule of quite high acidity. In temperate regions even the best draining only makes of them second-rate cultivable land with a high manurial requirement. In hot climates the felling of trees which accompanies cultivation so hastens the decomposition of the peaty material that the drained layers are speedily enriched and at the same time shrink to a fraction of their former bulk, a fact which should be borne in mind when draining and building are projected. There will certainly be some need for calcium and potassium, but it will not exceed that of normal soils, whereas the content of phosphoric acid and of nitrogen is usually well above that of mineral soils.

Such former forest peats, if of sufficient depth, are well worth cultivation. In India they have been used with success for the cultivation of tea and of oil palms. The latter is very commonly present as one of the native plants characterising the forest peat. When tall-stemmed growths such as palms are planted these loose soils show a defect in that after a certain period of growth the trees regularly fall down. This, however, is merely a blemish which, though giving a peculiar aspect to such plantations, does not reduce their good yields, since the fallen stems form fresh roots without further attention and calmly sprout upwards again. Successful

attempts have recently been made to avoid this trouble by planting dwarf varieties.

Of all plant formations on the earth the tropical and subtropical rain forest has without doubt the greatest yearly production of organic matter. Apart from upland forests this is the single formation that can be described as of primaeval growth. It is the true "primaeval forest" (*Urwald*) and its distinguishing features should be carefully ascertained, since the designation primaeval or virgin forest has been misused in hot countries almost as widely as the word "laterite", and this, as we shall see later, has frequently led to an erroneous valuation of local possibilities in respect to agricultural undertakings in the tropics.

To the European whose native woods reach a comparatively small height and produce a comparatively small bulk of vegetation any well-grown lofty forest seems of primaeval stature, whereas it may have nothing to do with the genuine rain forest and may indicate local influences and possibilities of cultivation quite other than those which the agricultural pioneer feels justified in inferring from the astounding abundance of plant growth. The tropical rain forest, which, with its subtropical counterpart, can alone claim the title of primaeval forest, varies in botanical composition very widely from place to place and requires a botanical expert to study the different kinds of plant. Its habitat, however, is the same the world over: wherever there is a high mean annual temperature combined with a rainfall not less than 80 inches in amount and evenly distributed throughout the year.

The peaceful aspect of wooded country elsewhere is absent here. Giant trees of fifty to eighty yards in height expand their crests far above the broken forest wall. Their pale gleaming stems effectively outline the vivid mosaic of foliage in which all

shades of green are mixed with red and violet tints. Epiphytes form a sea of flowers afloat in the airy heights like suspended gardens and reaching past four or five levels of plant growth up to the topmost crests in a search for light. Of the factors which make existence possible it is light for which there is the keenest struggle in the primaeval forest.

The big trees are characterised by very glossy leaves which share out the light by reflection. In the lower levels of vegetation pointed leaves are so shaped as to allow excess moisture to drain off on to the ground without injury to the plant The forest floor is thickly carpeted with a great variety of large-leaved bushes and ferns of which the whole structure reveals adaptation to the struggle for breathing-space in the eternal dampness of the forest, while countless creepers, often hundreds of yards in length, link up the various plants in fantastic tendrils and loops forming an impenetrable jungle.

Ordinary round stems, however deeply rooted, would break at the least wind under their own weight and that of the other plants they support. For this reason almost all the large trees of the primaeval forest have in the course of their evolution split up their stems into an elegant supporting structure consisting of so-called buttress roots, so that near the ground the trees are star-shaped in cross-section. Higher up they acquire a younger appearance and unite to a more or less round stem which thus rests on a protective basis of a hundred square yards or more.

The subtropical primaeval forest shows in principle the same relations, but is rather less luxuriant than that of the tropics and contains fewer creepers and buttress roots. The same is true of the primaeval forests, which depend on soil moisture instead of climatic moisture and often extend for considerable

distances along the banks of tropical and subtropical rivers. These are called gallery forests, and have occasionally misled even experienced investigators such as Stanley to speak of districts as covered with primaeval forest when the treeless steppe lies only a few miles, or even a few hundred yards, from the river-bank beyond a sharp boundary of forest.

The yearly production of fresh organic matter in the primaeval forest approaches one hundred tons per acre on a cautious estimate. In temperate climates there would result from this a layer of humus many yards thick. In the moist twilight of the tropical and subtropical primaeval forest an unbelievable company of tiny creatures, plant and animal, is at work consuming residues of the higher plants as they fall to earth. The destruction of organic matter proceeds so fast that it is a great rarity to find an eight-inch layer of what would ordinarily be called humus, and the layer of forest litter is correspondingly shallow. The "yard-deep humus layers of the tropical primaeval forest" are therefore either poetic fantasy or indicate that the primaeval forest has been confused with the forest peats already described, for which the name primaeval forest is in no way suitable.

As a rule, even where growth is most vigorous, the layer of litter or humus reaches only an inch or two, and immediately below it there is a bright red or yellow soil which apparently contains no organic matter if judged by ordinary conceptions of humus. This is only apparently the case, for almost without exception this coloured soil is rich in humus to a depth of several yards. Contents of humus running up to 10 per cent for the topmost layers are no rarity. In temperate climates they would impart a dark humus coloration to the soil.

The greater part of tropical "humic substance" is either colourless or only faintly coloured but

darkens very much on exposure to air. It is, moreover, very readily decomposed, and must consist for the most part of water-soluble constituents of plant refuse which quickly soak into the soil, so that there is not time for decomposition to set in. The nature of these organic substances of tropical soils is still completely unknown, but they must at least in part be strongly acidic in character. This is indicated not only by the exceptionally high acidity ($p\mathrm{H} = 3 - 5{\cdot}5$) shown to a depth of several yards by all primaeval forest soils formed on rock low in bases but also by the complete absence of lateritic or, better, "allitic" weathering in the upper layers of soil. Where organic acids bring about a strongly acid reaction allitic weathering is impossible, and in fact is not found anywhere, in Africa or Asia at least. A strongly acid reaction is the characteristic of primaeval forest soils in the true sense of the word, and is occasioned by the strongly acidic nature of the humus material formed there.

Where the original material was low in calcium, soils formed by the action of these humus bodies are mostly of a clay or strong loamy texture and are often greasy like soap; in a word, they are typical "siallitic" loams (Harrassowitsch). With light soils bleached sand and ortstein are present in the subsoil. The loams are usually bleached to a light yellow.

Where the original rock contained a large amount of bases the picture is entirely changed. Under these conditions the humus or in general the organic acids of the primaeval forest soil are saturated with bases derived from minerals and the reaction alters towards the neutral point ($p\mathrm{H} = 7{\cdot}0$). Even so the forest soil or forest humus remains faintly acid. At any rate in the course of thousands of pH tests on primaeval forest soils I have not met a single

exception. The texture of the soil now differs greatly from that just described. The organic substances have a cementing action on the soil particles and so impart an excellent crumb structure which extends to considerable depths. Plant foods are

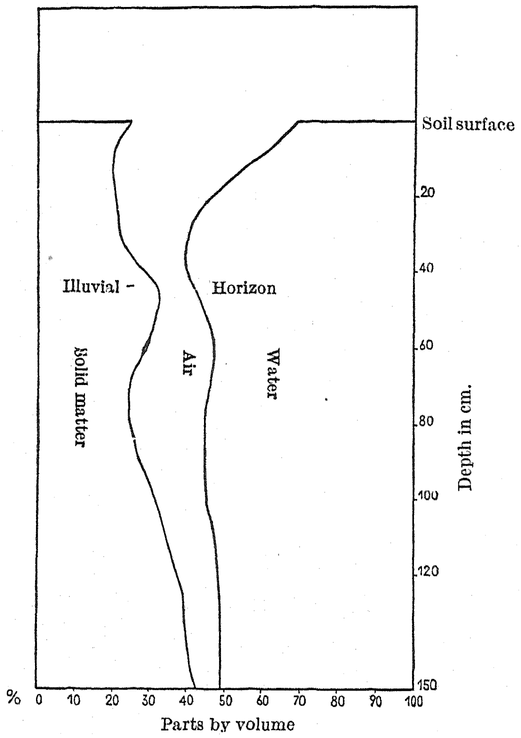


FIG. 10.

present in ample amount and the whole profile is therefore attractive in the extreme. Although the subject of soil profile will be treated in detail later, a diagram is given here in illustration of the preceding remarks. The diagram (Fig. 10) displays in striking fashion the partition of solid matter, water and air in the natural state of such a primaeval forest soil. The figures of the diagram

need no explanation. It is of course clear that biological factors are also largely concerned in this characteristic soil structure.

It should be noted that these soils often have a clay content exceeding 20 per cent, and that the sorption complexes at a weakly acid reaction (pH 5·6 – 6·5) are about 80 per cent saturated with bases. These are indeed the "inexhaustibly rich tropical soils" which are the dream of the agricultural pioneer. Unfortunately soils of this kind, of which the Dutch East Indies contain an example in their world's record tea soils, are by no means widespread. They are largely confined to areas of tuff and volcanic ash where the magma is rich in bases and must already have been taken up wherever transport facilities permit agricultural development.

For the rest, experience has repeatedly shown that these excellent soils will not withstand improvident agricultural exploitation, for this quickly robs them of their valuable qualities. On the other hand, no other tropical soil gives so profitable a return for good physical treatment combined with very heavy manuring. In spite of their high humus content the colour of these soils is fairly bright, a full red-brown that rapidly takes a considerably darker shade under cultivation. The lower layers are often bright yellow, although they contain considerable amounts of organic matter which has a quite disproportionate nitrogen content ($C/N = 6$). As illuvial horizon there is usually at a good depth a more or less dark-red zone, a sign that air penetrates to great depths in this soil. As would be expected, there are between this and the forest swamp soils all conceivable transitional forms depending on local conditions. *Natura non facit saltum.*

In the area of primaeval forest in the strict sense of the word, that is in districts where temperature

and moisture are continuously high, the forest may come to a stop in steeply undulating or intersected country. This circumstance shifts the soil climatic conditions of the forest and of the concomitant humus formations in which we are now interested, towards the savannah climate which is characterised by the monsoon forest. Even here the rainfall is still high, but is sharply divided into rainy periods and dry periods, whereas in the rain-forest area rain is fairly evenly spread through the year although there are definite maxima and minima. The dry periods may or may not be interrupted by small showers. On the slopes of the wet districts water soon runs off, and the upper layers of soil dry fairly quickly, with the result that there is, as it were, a succession of rainy and dry periods in place of the comparatively slow alternation of the monsoon climate.

The extent of monsoon forests over the whole world is much greater than that of the rain forests. Their chief characteristic is the well-marked leaf-fall that occurs with most of the trees at the beginning of the dry period. The number of varieties of trees and bushes is much smaller than that of the rain forest. Associations containing very few varieties are not uncommon. In the typical monsoon forest there are no buttress roots owing to the dwarfing of the stems and smaller development of foliage. The interior of the forest is lighter, and there is some surface grass which is almost entirely absent from the rain forest. There are, of course, all sorts of intermediate stages between this and the rain forest.

The annual production of organic matter in the monsoon forest may be estimated at about twenty tons to the acre; it is thus still very considerable. In waterlogged depressions these amounts are sufficient to lead to the formation of forest swamps

within the monsoon area. Outside the depressions, however, production of humus in monsoon forest is comparatively small. This is because the addition of leaf residues to the soil takes place chiefly at the beginning of the dry period, when there is no water to saturate the fallen leaves and cut them off from air. At the same time, since the forest roof is thinned, the sun warms up the ground and increases the activity of micro-organisms, which destroy organic matter at an enormous rate.

One finds also in monsoon forests infiltration of light-coloured organic substances extending sometimes to the depth of one yard. It is, however, much less than that of the rain forest. Signs of a well-defined humus layer occur only exceptionally in monsoon forests. Below an inch or two of more or less decomposed leaf litter there is either a quite thin layer of humus quickly passing into the red subsoil, or else what looks like purely mineral soil.

As will be described in greater detail elsewhere, the boundary area in which "siallitic" weathering gives place to "allitic" weathering is reached where the soil has a weakly acid and occasionally neutral reaction and where organic acids play a smaller part in weathering processes. The intermittently moist climate of the savannah is characterised by predominance of allitic weathering.

In order to avoid misunderstanding a definition is necessary at this stage, for the meanings attached to the words "savannah" and "steppe" vary widely with different authors. In what follows we shall understand by savannah those plant formations in which trees and bushes, in addition to tall grass, characterise the landscape. In this sense savannahs are to some degree detached monsoon forests in which lengthening of the dry period, often without change in the total rainfall, has reduced tree vege-

tation in favour of a grassy undergrowth. Unusual permeability of the soil sometimes leads to the same result as extension of the dry period, which is often coupled with dry winds injurious to trees.

The savannahs in this sense are not far behind the monsoon forests in production of organic matter. A cautious estimate would put the production at about twelve tons per acre per year. Except for the clumps of trees, which in humus formation stand on a par with monsoon or gallery forests, the savannah, flooded with light and heat, affords no possibility for accumulation of humus at the soil surface. All savannah soils appear to be low in humus, but nevertheless they all have to some feet depth of profile a content of colourless or fairly light-coloured organic matter in amounts not much below that of the monsoon forests. The same is true of the mixed scrub forest, which often alternates with the savannah within a belt whose limits of rainfall are between 45-60 inches. The mixed scrub forest is characterised by the occurrence of thorn bushes as isolated trees and never as the main member of the plant association.

When the tree cover gives way to clumps of trees or isolated trees so that grassland becomes a determining feature, the savannah has changed to tall grass steppe carrying trees and then resembles a park landscape, although it more often extends over wide areas as pure tall grass steppe. They reach their greatest development in West Africa and in Central and South America with a lower rainfall limit of about 25 inches. This rainfall is mostly limited to strong downpours within a rainy period which alternates with an almost completely dry period of about the same length. This is particularly the case with the typical forms of the umbrella-tree steppe and the umbrella scrub plus tall grass steppe and the so-called orchard steppe, which

is an intermediate form in the series leading to the low grass steppe.

The exception presented by the South American pampas, which occurs in regions receiving rain in almost every month, is only apparent, since the marked concentration of precipitation into isolated downpours is, as we have already seen, practically the same in effect as a marked alternation of wet and dry periods.

Beside the tall grass steppes, which are determined by climatic influences, are to be ranged the edaphic tall grass steppes, *i.e.* those which depend on conditions of topography or soil and which Engler designates as savannahs in the strict sense of the word. These form where heavy soil in depressions of greater or smaller extent is acted upon from time to time by abundance of water. Such climatic islands of soil can, of course, be found in definitely arid districts and may be of considerable size. They may be recognised by two distinguishing features even when one knows nothing of the climate of the district. The soil is invariably heavy, is often a deep cracking clay, and is always dark gray or almost black in colour. This dark colour is no more a sign of high humus content (*see above*) than the usual red colour of the climatically determined tall grass steppe is a sign of low humus content.

Humus layers in the ordinary sense of the word are completely lacking in the region of tall grass steppe, and the invisible humus content of the soil is also low for the most part. Only the islands of forest and scrub lying within the tall grass steppe show as a rule a rather higher humus content, as does also the patch of ground lying directly in the shadow of a single tree. This has, of course, no practical importance unless one is dealing with a fairly thick cover of trees.

It is interesting to note that in districts where

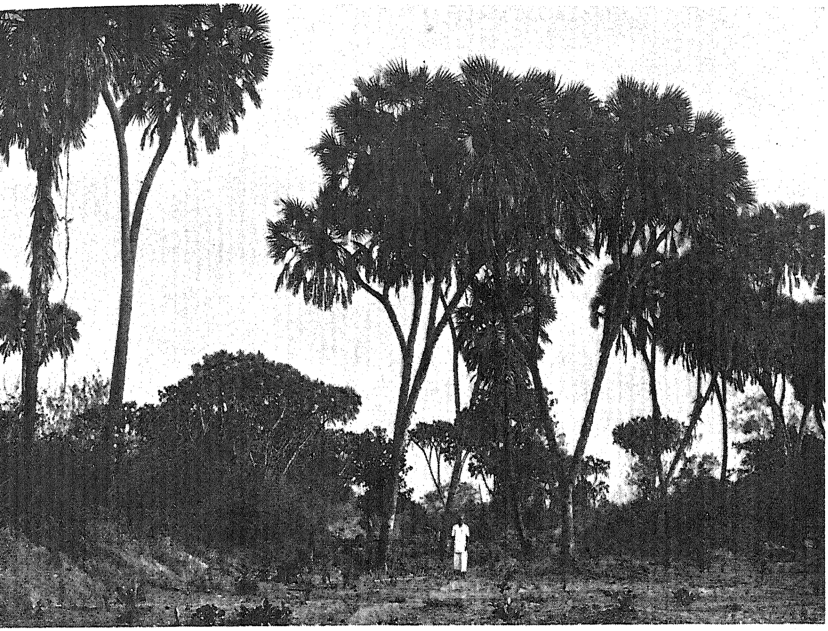
climatic influences have determined the tall grass steppe the clumps of trees or scrub prefer the local depressions, and the bigger ones are to be found in old stream-beds which sometimes carry ground water at not too great a depth. In such cases the soil is usually darker in colour. Where the tall grass steppe is of edaphic origin, on the other hand, the islands of trees or scrub stand as a rule on elevations (on termite heaps for choice), for only there is the soil sufficiently permeable and sufficiently well aerated to permit growth of tree roots. In spite of its higher humus content the soil in such places is very commonly red, *i.e.* oxidised, and these localities thus form the only spots of colour in the pale yellow of the dry grass and its background of gray soil.

In Africa tall stemmed acacias, such as acacia seyal, and mimosas are characteristic plants of the tall grass steppe when of edaphic origin. Tamarinds and dôm palms (*Hyphaene thebaica*) are of local importance, occurring in the vicinity of streams of which the inundation areas are commonly covered by tall grass steppe of edaphic origin.

Though formation of humus is small in the region of tall grass steppe, it is very much less in the definitely arid areas in which with an upper rainfall limit of 25 inches there is hardly ever any excess of water.

If for our present purpose we exclude South America down to 30° S. because its comparatively high rainfall permits vigorous vegetation, we find that no other vegetation zone in the world is so vast as the dry forest and steppe. Moreover, in no other part of the world is the physiognomy of the plant associations of so varied a kind or so greatly modified by minute topographical or edaphic factors which can hardly be detected by the eye, and which in every case are doubtless connected with local varia-

PLATE III



THORN BUSH WITH DÒM PALMS (HYPHAENE THEBAICA)
(East Africa)

tions in the supply of water for the plant cover. The smallest declivities are converted into soil climatic islands if they collect enough water to cover them, and so permit the appearance of plant formations which do not really belong to the steppe district. The change may be due either to increased moisture, which promotes disproportionately vigorous growth, or to the salt content of the water, which further intensifies adverse conditions so that only salt-loving plants and plant associations can maintain a foothold. A similar positive factor is to be seen on the slopes of mountains within the steppe district. Although the hills are not nearly high enough to receive heavier rainfall than the surrounding country, the run-off of water following scanty rain collects on the lower slopes and at the foot of the hill and provides conditions in which mixed scrub can grow. Almost all mountains and hills in the steppe area show this effect and are adopted by the natives for their settlements. The exposed flanks of mountains or hills are usually in sharp contrast, and either carry typical desert plants or are bare of any higher vegetation.

Dry forests and scrub occur in two very different forms. On the one hand, they may consist of a light cover of trees with scanty foliage and of varieties which for the most part yield aromatic oils and resins. They have as a rule no woody undergrowth and no cover of grass. Specially typical are the Eucalyptus and Casuarina shadeless forests of Australia, in which the stems often reach a gigantic height, and the horribly monotonous Myombo forests of the dry parts of Central Africa.

Of much wider distribution than these sparse forests is the thorn scrub, or, more generally, dry scrub forest chiefly composed of various thorns. This occurs over all the dry regions of the world, and, in spite of local variations in plant composition,

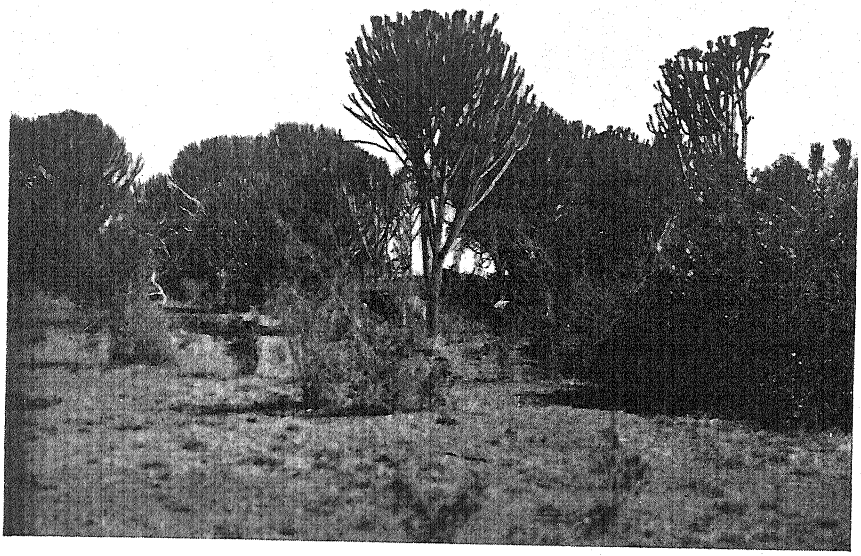
maintains a uniform character. Extreme curtailment of leaf-evaporating surface and the most rigid economy of water is the main feature. Only for a few weeks in the year does this bush put out new green leaves; for an even shorter time here and there an astonishing display of flowers appears to make up for the months of deadly gray monotony in the dry season.

The low grass steppe in some measure duplicates the variations of the tall grass steppe, from which it is distinguished only by its shorter grasses and the appearance of xerophytic plants, the latter being a very typical feature.

Whereas in dry bush country cacti and euphorbiae (*see* Plate IV) are unmistakeable characteristic plants, in the steppe their place is taken by their smaller associates, all sorts of plants with succulent stems or leaves, and especially by a host of bulbous plants. When these are in flower on the steppes of South Africa or Asia they present for days on end a splendour of bloom which, if once seen, is never forgotten (Plate V). Like the tall grass steppe, the low grass steppe also supports certain typical trees which occur as clumps or alone in places where the soil conditions of the steppe are presumably specially favourable.

Occasional giant forms are to be found. Most of them are adapted to the dry regions by possessing a fleshy trunk. The cotton tree (*Ereodendron, Ceiba pentandra* Gaertn.) is quite cosmopolitan and occurs in Africa as well as in Asia and America. The baobab or monkey-bread tree (*Adansonia digitata*), of which the trunk may reach a diameter of ten yards, is confined to Africa, while Australia has the aptly named black-boys (*Xanthorrhaea arborea*) with its curious growth habit. Of palms occurring in the steppe area the dôm palm (*Hyphaene thebaica*; *see* Plate III) is a striking member. It may either

PLATE IV



DRY SCRUB WITH EUPHORBIA CANDELABRA
(Central Abyssinia)

occur alone or be associated with *Euphorbia candelabra*. For the rest, steppe country throughout the world is the domain of acacias and mimosas in countless variety, ranging in height from dwarf types to tall-stemmed trees, with broad umbrella-like crests. Massive figs with dark-green foliage, the holy tree of India, disclose the presence of ground water often at a small depth.

Throughout the dry regions, whether they carry light forest or steppe vegetation, the production of organic matter is small. Humus formation is limited, however, not only by scanty provision of organic matter, but by an even more decisive factor. The brittle leaves of grass are broken to dust in the hot winds of the dry season and are immediately swept away, falling to earth again far from the place in which they grow. Some fragments are left, but these, as may be observed in any steppe, remain for a while practically unchanged, since the upper layers of soil are hardly protected from the sun by the scanty growth of grass and become so hot and dry that no lower organisms can thrive there. The first rains, however, set up a sheet-like flow of water which carries the grass fragments into the nearest declivity, where decomposition rapidly ensues under more favourable conditions of moisture.

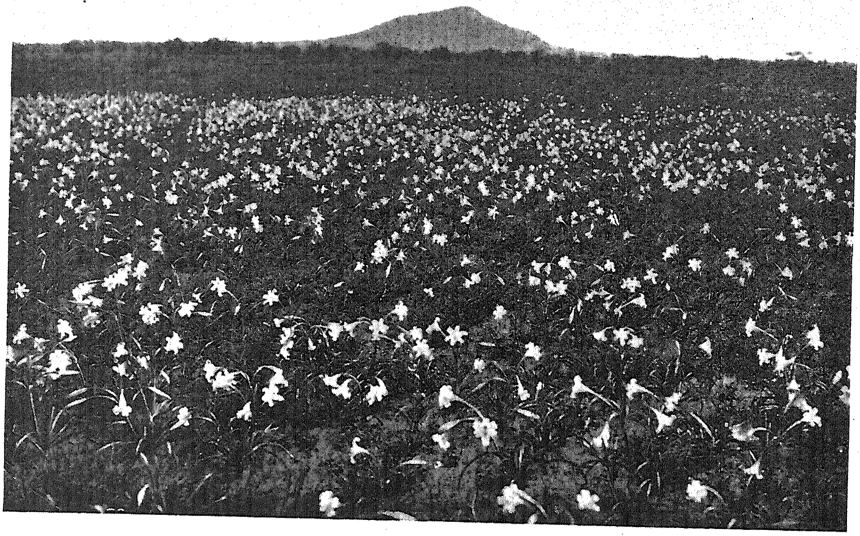
Very commonly, however, vegetation in steppe country contributes nothing at all to the organic matter of the soil, for grass fires are more frequent here than in tall grass steppe or savannah and burn up all dry plant material. Grass fires lay waste thousands of square miles of steppe country every year. They are often started by human agency, for the nomad peoples of the steppe set the dry grass alight in order to obtain fresh pasture, which quickly springs up on the burned land. In other cases lack of attention to domestic fires has been responsible. Action on the part of govern-

ment can be of great practical value, especially where it does not conflict with requirements of the native population for grazing, and in the majority of tropical steppes this is only exceptionally the case. Even in spite of precautions grass fires are common enough, since lightning causes outbreaks. This does not set the low grass alight directly, but when a tree is struck it may catch fire and fall and then the damage is done. As it happens, I have myself twice seen this occur, and this cause of fire cannot therefore be unusual.

It is not surprising that under these conditions the organic matter of steppe soils should have a peculiar and quite characteristic composition. This holds also for dry bush lands in which, *mutatis mutandis*, the same conditions are at work. In steppe and dry bush lands there is always some minute infiltration of organic matter. The curious feature is, however, that practically fresh and dry plant fragments are associated with an appreciable amount of charcoal, which is in fact a typomorphic mineral of steppe soils.

The only steppe soils which form an exception to this rule are those which develop in regions bordering on a savannah climate and on a primary or secondary rock material which is specially rich in bases. Under these conditions which include a rather moister soil climate the upper layers of the soil profile are enriched with dark organic material which has the character of highly saturated humic substances. This is formed during alternation of leaching and concentration of the soil solution, but how precisely decomposition occurs remains at present entirely obscure. Where the predominating base is calcium, black earths are formed. These extend far into temperate climates, forming some of the most fertile soils in the world, including the famous *regur* of India and no less famous

PLATE V



FLOWERING LILY-STEPPE (SOUTH AFRICA)
(Umbrella scrub in background)

tschernosiom of Russia. On the other hand, when alkalies predominate in the parent rock—taking rock in its widest sense—dark, strongly alkaline soils, for the most part of very questionable fertility, are formed. Where these develop on deposits of ash and carry grass or fern vegetation they sometimes resemble fen soils. A special form of black earth having a calcareous basis has already been mentioned under the heading "Secondary Rock Formation in Soil". Related forms are of more than local occurrence since they are distributed over quite wide areas occupying bigger depressions, which in the case of Africa usually carry instead of grass herbaceous steppe vegetation together with *Acacia fistula*.

In the steppe lands under consideration formation of humus is certainly very small, apart from the exceptions just noted, but is nevertheless general. As the climate becomes drier or as salts unfavourably affect conditions of plant growth this weak production of humus becomes a local phenomenon limited to the immediate neighbourhood of shrubs and bushes within the desert steppe, salt steppe or desert. Each single plant then constructs, as it were, a little world for itself and by slow degrees forms its local "humus soil", of which the humus largely consists of plant remains permeated with salt and but slightly decomposed. Tamarisks which occur in salty land throughout the world are an example. This humus formation has, of course, no practical importance. In the true desert humus formation is practically nil, although the desert is entirely bare of plant life only where moving sand dunes or rock debris form the soil surface.

With the possible exception of the primaeval forest, the plant formations which have so far been discussed as sources of humus may be re-

garded as primary in the sense that no survivals from periods with other conditions are found. There are, however, obvious new formations which play an important part in the tropics and subtropics. Forest land, for instance, is changed to secondary forest and scrub, and still more noticeably to savannah and steppe. Apart from natural catastrophes such as volcanic eruptions, one powerful factor tending towards this impoverishment of soil is human activity, which hews gaps in the forest cover and then abandons them to Nature. Enormous areas are thus laid bare, and it is not surprising that with native methods there ensues, especially where the land is but thinly populated, an immeasurable loss in the productivity of the soil. What subsequently grows on the denuded areas entirely depends, of course, on local conditions, and the same is true of humus formation under secondary growth of this kind. The secondary formation contains at the best but a trace of the original humus, for with heavy cutting of timber and bad soil management even a deep bed of humus vanishes in the tropics and subtropics within a few years.

The secondary savannahs of the East Indies are specially typical of devastated forest land. In the Malayan Archipelago all other growth is displaced by *alang alang*, the most feared weed in all East Indian plantations; its peculiarities have already been discussed in connection with incipient pan formation. In Africa and America so pronounced an overgrowth of abandoned fields by a single plant species is almost unknown.

Discussion of the various kinds of secondary vegetation would merely entail repetition of what has already been said. From the practical point of view it is important to note that soils of secondary plant associations are as a rule more or less im-

poverished, and are often particularly ill-provided in respect to humus. This is not so serious where it is possible to improve the land by artificial means, but in general particular care should be taken in choosing land under secondary vegetation.

It is unnecessary to discuss humus formation in plant associations which are of purely local occurrence, such as mangroves and swamps.

CHAPTER IV

CLIMATE, RELIEF AND VEGETATION IN THE FORMATION OF TROPICAL AND SUBTROPICAL SOILS

THE study of extensive land areas led to recognition of the dependence of soil formation on climate, and this, as was emphasised in the introductory chapter, marks the birth of modern soil science. Blanck justly says: "In this way modern views on soil link up with the names of Dokutschajeff, Sibirceff, E. W. Hilgard and F. von Richthoven, who not only gave a special orientation to the development of soil science but raised it from the purely descriptive and practical stage to the position of an independent scientific discipline".

Lang in 1915 was the first to give quantitative expression to the original qualitative statement of the relation between soil and climate. Ramann, in conformity with Russian and American workers, had regarded temperature, precipitation and evaporation as the main factors of climate. Lang made the not altogether justifiable assumption that variations of temperature and evaporation are usually concordant. He accordingly combined precipitation and temperature in his "rain factors", by means of which the soils of the globe are assigned to various climatic regions.

The rain factors are obtained by dividing the rainfall (in millimetres) by the mean annual tem-

perature (centigrade) of the district. There should then be formed:

With rain factor exceeding	160 . .	Peat soils.
,, ,, between	160 and 100 .	Black earths.
,, ,, ,,	100 ,, 60 .	Brown earths.
,, ,, ,,	60 ,, 40 .	Yellow or red soils and laterite.
,, ,, below	40 . .	Arid soils.

This formulation undoubtedly opened up a fruitful line of thought. Further investigation has indeed shown that the scheme is not always correct and requires considerable modification; but that, after all, is the common fate of almost every new idea, and in no way detracts from the merit of its originator.

A clue to the improvement of the factors was found by Meyer in the consideration that the parallelism between temperature and rate of evaporation, though exact in favourable cases, was often non-existent. He based his observations on Europe, where differences of temperature play a minor part, and came to the conclusion that, second to precipitation, the saturation deficit was the most important factor as a measure of evaporation. He gave the name "N-S quotients" to the figures obtained by dividing precipitation by saturation deficit.

The factors both of Lang and of Meyer are valuable guides for the inspection of wide areas, and are specially useful if derived from the maxima of climatic factors which imprint their mark on soil. Exceptions are, however, too numerous not to invalidate the rule. In this connection Jenny justly observes that while it is certainly legitimate to take some function of precipitation and evaporation as representing the moistening of the soil, the function should not be made to include the completely independent factor of temperature. In regional distribution he regards soils as functions of two

independent variables, moistening and temperature, and has already achieved outstanding successes in fairly big areas such as North America and Europe. Far from exaggerating the dependence of soil character on climatic conditions, he is careful to state that a purely climatic view-point does not suffice for soils. He is thus in full agreement with the thesis that soils must be classified by their characters, although he does not abandon the wide genetical view-point which makes possible a general scheme of classification.

This conception is in close agreement with that of American workers, and more particularly with that of such Russian authors as Glinka, Kossowitch, Vilenski and others, who explicitly recognise the importance of a number of factors limiting the influence of moisture and temperature on soil formation. Such factors are the character of the parent rock and preponderating influences such as long-continued waterlogging, which leads to the formation of peaty and swampy soils. The character of the parent rock, however, can hardly be included in a regional climatic scheme, and it therefore becomes increasingly evident that the evolution of soil types is determined not by the climate of the air but by the soil climate, which is the product of air climate and local conditions. It is of course clear that moisture and temperature conditions within the soil must influence soil formation and soil processes to a far greater extent than conditions outside the soil. We have then to consider the soil climate of tropical and subtropical areas, and shall find that the available information is mostly qualitative since this subject has not yet been thoroughly investigated.

Temperature relations are comparatively simple and are readily summarised.

Even in temperate regions fluctuations of tem-

perature are limited to a fairly shallow depth. Daily variations of decreasing amplitude extend to a depth of about a yard, while yearly variations escape detection at a depth of thirty yards or less and have so great a lag that surface and subsoil changes are completely out of phase. At the same time, in temperate regions the yearly variations in subsoil temperature are very large. In the tropics, on the contrary, they are very small, ranging from a fraction of a degree to just over ten degrees for latitudes 30° North or South. The result is that, as a rule, in tropical and subtropical regions at a depth of 1·5 yards in the soil the mean annual temperature remains constant at values which are shown below:

At the equator	26·2° C.
10° N. or S.	26·5° C.
20° N. or S.	25·0° C.
30° N. or S.	19·4° C.

It thus appears that at a latitude of 30° North or South the constant subsoil temperature is 14° above the mean temperature of central Europe, while at the equator the difference is 21°. This means that the course of chemical changes in subsoil of the tropics is three or four times as fast as in Europe.

The character of temperature relations in soil layers lying above the zone of constant temperature is of course determined, in the first place, by the proportion of radiant energy which the soil receives from sun and sky. On this depend the degree of heating by day and of cooling at night. Between latitudes of 30° North and South the average daily income of radiant energy is 3500 kilocalories per square metre. At midday the radiant energy ranges from 0·02 to 0·028 calorie per square centimetre per second, and this figure does not include diffuse radiation from the air. It follows from this that a black body exposed at midday to the rays of the

sun must reach a temperature of 80°-90° C. Pechuel-Loesche and Vageler have in fact recorded temperatures of 84°-86° C. for the soil surface in the Congo and in East Africa, and similar figures have been registered in other tropical and subtropical regions.

Bare soil radiates heat at night and often falls below the air temperature, which in the subtropics is not especially high and in deserts may actually fall to within a few degrees of zero. The result is that the daily amplitude of temperature changes in the soil surface may be as much as 60°-80° C., which far exceeds corresponding variations in temperate climates and, as we shall see later, has an overwhelming influence on the movement of soil water.

This, of course, is only the case where such temperature variations occur, for it will be understood that these enormous fluctuations of the soil climate take place only in bare soil which is directly exposed to the sun. A further condition is that the soil must be dry, for otherwise evaporation of water counteracts the surface heating effect to such a degree that even in the hottest districts the surface temperature does not then exceed 50° C.

In deserts the soil is both bare and dry, and it is practically so in the low grass savannahs. It is here that temperature extremes make plant life impossible and restrict the activities of micro-organisms, at any rate in the upper layers of soil. To this may be traced the frequent complaints about the feeble "activity" of the surface soil. The temperature extremes occurring in bare soil of the tropics explain also the exceptionally deleterious effect which ill-considered felling of trees and neglect to grow shade crops on unused fields exercise on the surface soil of tropical regions. As a result of the influx of radiant energy not only does the microflora die, at any rate in the surface layers, but also any humus

that is present is then literally burned up. It is changed to the finest organic dust, which is in part completely oxidised and in part leaves a residue of humus charcoal, as may be seen in almost any badly managed soil of the hot belt. The widely held view of native cultivators in the Dutch East Indies that felling of tree cover for a period of three years, combined with exposure of the soil, is enough to destroy the richest bed of humus is precisely what one would expect from such a procedure. It is unfortunately true that even now unreflecting introduction of European practice in the matter of bare fallow occasions much damage in many tropical regions.

Even in the tall grass steppes the effect of shading is sufficient to limit maximum surface temperatures to about 40° C. In bush land the temperature is still lower, while lowest temperatures and least fluctuations are found in the primaeval forests, where soil temperatures are much the same as air temperatures and, in extreme conditions, are even a little lower.

In the belt of the tropics and subtropics soil temperature and the amplitude of its fluctuations have, therefore, little to do with climatic temperature but are primarily a function of shading by vegetation. Air climate from this point of view is only effective in so far as it roughly determines the lower limit of temperature. Even in extreme cases soil temperatures are only a few degrees below this limit.

What, then, is the position as regards soil moistening or soil moisture as the second major constituent of soil climate?

If the entire tropics and subtropics were plains bare of vegetation we should have the equation: moistness of soil climate equals moistness of air climate. The difference between precipitation and evaporation would be an accurate measure of soil moisture and climatic soil belts would encircle the

tropics in ghastly monotony. In point of fact nowhere outside the tropics is there such complete lack of the regular arrangement of humid and arid soils which theory demands; we find instead, in any traverse of the hot zones, a mosaic of soil types which frequently exceeds all theoretical limits. Examples typical of what is expected of the locality on theoretical grounds are rarer than in any other climatic region. Even if one abandons systems of soil classification which are based chiefly on climate, and takes into consideration what Glinka calls endynamomorphic factors, the infinite variety of Nature still eludes every strict system that has hitherto been proposed. There are indeed broad lines of agreement between theory and fact, but a cursory enquiry into details very soon reveals more exceptional than "normal" soils, and this is true even when one takes into consideration, as we have just done, temperature differences between air climate and soil climate.

There can be no doubt, therefore, that while for given temperature conditions moisture is the most important factor in soil formation, yet just as soil temperature is largely independent of air temperature, so also soil moisture in the majority of cases seems to be even less dependent on the humidity of the air. Now within limits set by climate, soil temperature is determined by vegetation, and this has a powerful influence in two different ways on soil moisture also.

One may assume that, as a rule, about four hundred tons of water are required for the production of one ton of dry organic matter. The consumption of soil water which, as we have seen, is the sole moisture factor active in soil formation, varies according to the mass production of the natural vegetation from nil in the deserts to 2500 tons per acre in the primaeval forest. One ton of

water per acre corresponds to one-hundredth of an inch precipitation, from which it can be seen that where vegetation is heavy a considerable fraction of the rainfall is thus consumed and, accordingly, is to be regarded as a very limited and transient contribution to the soil moisture.

A further fraction of the rainfall is lost at the moment of precipitation by evaporation from the plant surface. In thickly wooded country 20 per cent as an average is not perhaps too high an estimate for this item, for while loss by evaporation from trees and so forth is certainly much less during heavy downpours, yet in thick forest, even in temperate climates, a reasonably heavy shower does not reach the ground at all. Anyone who has made his way through primaeval forest is familiar with the experience of hearing the rain beat on the high leafy roof while not a drop falls to the ground, so that only the sound of the drops against the leaves and the increased darkness show that it is raining "outside".

In open country loss by evaporation at plant surfaces is of course relatively small. Here, however, in contrast to woodland or forest, the soil surface is not protected from evaporation by shading and low saturation deficit; in fact, no sooner is the rain over than the sun beats down again. That part of the rain which is lost in wooded country as it strikes the trees is more than accounted for in open country by evaporation from the soil which sparse plant growth inadequately protects. In round numbers, a further 30 per cent of the total precipitation may be written off as consumption by the plants through direct or indirect evaporation, so that the total loss will seldom be less than 40 per cent, and will often be over 50 per cent. This applies to regions of heavy rainfall; where rainfall is light and where the climate is such that evaporation exceeds

precipitation, these conditions accentuate the deficit in so far as soil climate is concerned.

On the other hand, vegetation helps to conserve water in so far as it impedes surface flow, the effect being greater as the vegetation is more dense. In this matter of surface flow we reach the most weighty item in the economy of soil moisture, and one which I do not hesitate to regard as primarily determining the mosaic character of tropical soils.

The run-off of rain water has been studied with special care in temperate climates. In tropical and subtropical areas corresponding investigations have been far from complete, but yield at once a result which contrasts very strikingly with those of the temperate zones. The figures for run-off are not only higher, which is an obvious consequence of heavier rainfall, but they are also a larger percentage of the precipitation. With equal rainfall a much higher proportion of the precipitation flows away in the tropics and subtropics than is usual in temperate climates, although in view of the strong evaporation one would expect the contrary. Run-off coefficients are specially high in semi-desert or desert climates, and the traveller who visits such areas during the rain reason may often obtain drastic evidence of this without making any special measurements, for the first flush of flood in rivers which have been dry for months comes down in a wall of turbulent waters and conveys a striking demonstration of the powerful run-off in such districts. The fan-like deposits at the mouths of intermittent streams of arid countries are no less impressive, for they could only be formed by the sudden onrush of huge masses of water.

The reason for these happenings is evident. It is the extreme heaviness of rainfall in most tropical and subtropical regions, which far exceeds ordinary figures for temperate regions. References to the

intensity of rainfall are to be found in almost any account of travels in the tropics. "The rain came down in torrents" is a common phrase of such narrations, and if reduced to figures often corresponds to a precipitation exceeding 5 inches in an hour. The exceptional importance of this high density of rainfall in respect to water economy of the soil in the tropics and subtropics is nevertheless hardly appreciated as yet.

Rainfall slightly exceeding half an inch per hour is wholly absorbed only by very light soils, and any higher rate leads to surface run-off even where slopes are very gentle. On heavy soils the same density of rainfall produces pools and local streams even where the ground is comparatively flat. In specially level districts the whole surface may be waterlogged for a time, and if there is a slight slope the whole sheet of water begins to flow. When the amount of rain greatly exceeds what the soil can absorb during the period of precipitation—the excess is a very simple function of the rate of rainfall—the slowly moving sheet of water becomes a definite flood, and the tiny watercourses become miniature torrents wherever the land slopes more steeply. This flow of water has an important effect on the profile structures of tropical soils, which will be discussed later in detail.

Here we need only note that wherever sheet flow and rivulets can thus be produced, and this is the case even on the most gentle of slopes, by far the greater part of the water is carried off from the upper slopes, because it has not sufficient time to penetrate the soil. For this reason all slopes in regions of heavy rainfall and, accordingly, almost all slopes in the tropics and subtropics are, in so far as soil climate is concerned, forced into more arid zones with temperature conditions controlled by the vegetation and modified by the direction of

the slope and the amount of radiation received. At the foot of the slopes, notably at the foot of hills and mountains, and, to a smaller degree, beside any minor ridge, water penetrates more readily. This is specially the case where the slope is so steep that the flush from the top carries down detritus of soil and rock, forming a local deposit of coarse-grained and fairly permeable material. In such a situation the soil climate is comparatively humid, even if the district is an arid one, and as a consequence there result soil formations typical of these conditions, but atypical in respect to the climatic region. This commonly goes so far that even exposure to the prevalent rainy quarter plays a part. In dry districts, for instance, one very often finds that only the moister side of elevations and hills has a coating of red earth and supports a more vigorous vegetation than is congruous with the climate.

Definitely humid conditions occur in all depressions except where these are relatively of too wide extent. Water moving across the gentle slopes carries down much fine clay-like material, and accordingly soils of such depressions are usually fairly heavy and only feebly permeable to water. By far the greater part of such depressions, even within dry areas, is thus transposed to Glinka's class of soils formed under conditions of intermittent excess moisture. The nature of the parent rock and the amount of organic matter carried in or grown on the spot then determine whether a reduced soil, a black earth, a swamp or a salt basin will be formed there. If the depression is so big in relation to the high land that only negligible amounts of water are brought in, or if the area is a flat tableland, then, and only then, is there close agreement between air climate and soil climate. Even so the parallelism is modified in respect to

moisture by the nature of the local rocks, and more particularly by the permeability to water of the topmost layers of soil, for evidently if permeability is low there will be fairly long periods during the rain season when the rate of precipitation is sufficiently high to lead to continued waterlogging and to corresponding changes in the soil.

Thus, while soil types of the tropics are in a general way conveniently classified in relation to the atmospheric climate of the district in question, vegetation, distribution of rainfall, local topography and nature of the parent rock have so great an effect on the detailed development of the soil that these secondary influences usually completely mask purely climatic influences, and certainly have a far greater effect in the tropics than in temperate climates.

The question as to why a red colour is so characteristic a feature of moist tropical areas has been variously answered by different workers, and is still far from a final solution. Most authors correctly regard dehydration of iron hydroxide and lack of coloured humus substances as being chiefly responsible. This is a matter of temperature. It is possible also that mixtures of iron sols and gels with those of silica contribute to the intensity of the red colour of tropical soils by their high colouring power.

There still remains the problem as to why the most highly oxidised iron compounds should be formed so rapidly and in such large amount in the tropics. Older writers connected this with the nitric acid content of rain, which is a natural inference from the frequency of thunder-storms, but latterly this idea has been much discredited at the instance of Lang. This appears to me to be a mistake. The amounts of nitric acid and of oxides of nitrogen which are added to the soil of the tropics and sub-

tropics by rain should not be ignored, as has recently been shown by the very careful investigations of G. Capus in Indo-China. In tropical regions of heavy rainfall, about 30-35 pounds of pure nitric acid are added per year and per acre by rain. The accompanying diagram shows the distribution of this amount for Indo-China, and includes

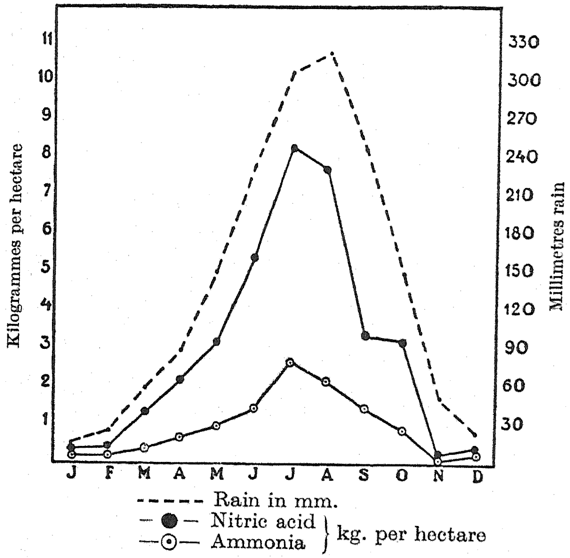


FIG. 11.—ADDITION OF HNO_3 AND NH_3 BY RAIN IN INDO-CCHINA (CAPUS).

also the amount of ammonia carried down by rain. The latter varies considerably from place to place, since it is dependent on secondary factors, such as industries, vegetation and so forth.

It is sufficient to note here that it cannot be immaterial to the intensity of all oxidation processes in the soil when such quantities of one of the most powerful oxidising agents are continually poured on to the soil. Oxidation is assisted by hydrogen peroxide and ozone which are produced in the soil itself

during evaporation and processes of decomposition. Addition of nitric acid is not, of course, the only reason for the intensity of oxidation in the tropics, but one should not at any rate pay too little attention to this factor.

CHAPTER V

THE FORMATION OF TROPICAL AND SUBTROPICAL SOILS

(1) Rock Weathering

The expression "weathering" is one of the commonest terms of ordinary speech, and is often regarded as being equivalent to soil formation, which is indeed true in a sense. If, however, we compare the actual meanings of "weathering" as used by different authors, we find almost as many variations as there are authors, which is, of course, no uncommon experience in the case of abstractions. Almost each individual has in mind a certain complex idea which he is not always able to define, and there is great divergence of view as to what is meant by weathering as a synonym for soil formation. Blanck in his "General Theory of Weathering" (*Handbuch der Bodenlehre*, vol. 3) has so stressed this diversity of opinion that discussion here would merely be a repetition of what he has said. As the outcome of all recent discussions on the idea of weathering we may perhaps take the following as a definition and base on it further consideration of soil-forming processes in the tropics:

From a physical standpoint weathering consists in the loosening and crumbling of rock under the influence of climatic factors with production of loose granular material, which is finally reduced

to colloidal size. From the chemical standpoint weathering consists in the conversion of rock components and organic remains into compounds, usually of gel character, which are either in equilibrium with those local physical and chemical conditions which represent the soil climate or more or less rapidly approach that equilibrium.

Weathering therefore does not include any changes in rock, whether physical or chemical, which are not induced by climatic factors and by concomitant processes among which the action of living creatures is important. Hydrothermic and other metamorphisms of rock are thus excluded. So also weathering does not include any processes which can be described as transport of material liable to weathering. Such transport is of fundamental importance in respect to the formation of deposited soils.

In the sense of the foregoing definition the product of weathering includes everything that is formed *in situ* from material susceptible to weathering, whether organic or inorganic in nature. Special emphasis should here be placed on the words "is formed".

We may with advantage use the terminology of Harrassowitsch, who was the first to clear up these definitions. Of the products of weathering formed under the influence of climatic factors there remains in the place of formation, or more generally in the domain of the weathering process, only what Harrassowitsch calls the *Frachtrest*, *i.e.* a residue of non-transported material. This consists of soil-forming material which has not yet suffered decomposition together with exhausted material, and also of substances immediately precipitated in the place of their formation by reason of their insolubility in the solution produced by weathering.

Among such substances are salts which are intrinsically soluble but which separate out owing to occasional lack of solvent, in this case, water. By *Fracht*, *i.e.* cargo, Harrassowitsch means material carried away by the solution produced by weathering. This solution may be regarded as a more or less turbid stream in so far as it contains not only dissolved substances, salts, bases or acids in molecular or ionic dispersion, but also suspended bodies, such as particles of clay and all kinds of material in colloidal dispersion. This last is of special importance. The *Fracht* may, of course, sometimes be completely removed by the stream of water, but it more commonly is an important factor in soil formation in other layers of the soil, for example in adjacent layers of the profile or in depressions.

The weathering solution and weathering residue, that is, the *Fracht* and the *Frachtrest*, are always in chemical equilibrium, excepting only in cases where the time of contact between the two components is too short for establishment of equilibrium.

It is evident that weathering is an exceptionally complex process in which all kinds of physical and chemical reactions are involved. This intimate association makes it uncommonly difficult to present a survey of the weathering process, since we have to consider the various items in succession and not in conjunction. This must be borne in mind throughout the following discussion.

(a) *Physical Weathering of Rocks*

We may regard the simple breaking down of rock into its mineral components as physical weathering in a narrow sense when this occurs without change in the components themselves, or as a

further step we may include the crumbling of the various minerals into smaller fragments.

In temperate climates one of the most powerful agents of such disintegration is frost. This is completely absent in the tropics and subtropics, but we have instead the no less vigorous action of weathering by heat. This depends not so much on the absolute heights of temperature attained by rock exposed to the sun, but on the abrupt variations in temperature the extent of which has already been mentioned.

The specific heats of rock components vary between narrow limits, and so also do their coefficients of linear expansion, which are only a fraction of a millimetre. These small differences are, however, sufficient not only to release stresses originally present in the rock as the mass heats up or cools, but also to set up new stresses of considerable magnitude. On this account granular rocks which are composed of many different mineral species readily break down with continued heating and cooling to rock dust. In this disintegration an important part is played by the different colours of the various components, which lead to differences in rate of heat absorption by the different minerals.

Temperature weathering is not, however, limited to this mode of action. According to Penck the volume expansion of a cubic metre of rock is about 14 cubic centimetres for a temperature difference of 70° C. A difference of this amount readily occurs in the tropics and subtropics between the surface and the inside of an exposed mass of rock owing to the slow conduction of heat through rock. De squamation or the cracking off of layers of rock results from this, as may be observed by any visitor to dry districts where scanty vegetation permits strong insolation of the soil. Granites and metamorphosed granular rocks are specially liable to

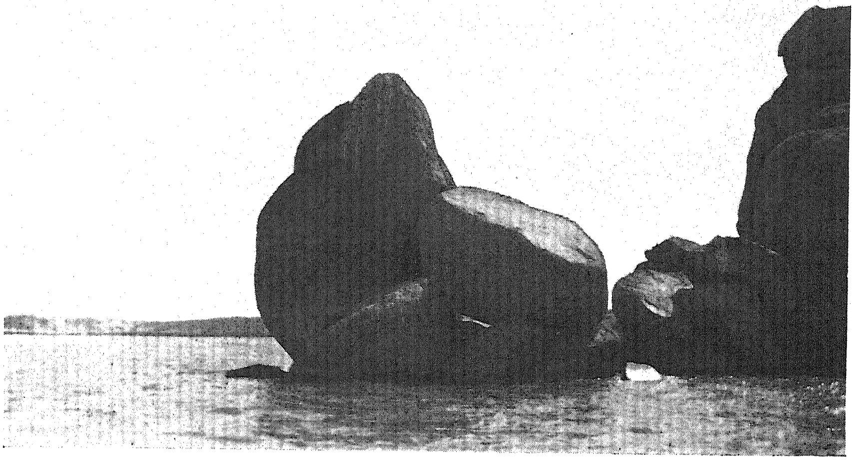
this kind of fracture, and the shells of rock so split off are often several square yards in extent. With compact rocks the phenomenon is usually restricted to the shaving off of fine layers from the surface, as can be directly observed when cold rain falls suddenly on the heated surface.

The splitting of large rock masses (*see* Plate VI) is also a consequence of strains set up by differences of temperature, and is to be regarded as analogous on the large scale with the breakdown of mixed rocks to dust as was mentioned above.

A rather different explanation should perhaps be offered for the cleavage of siliceous and similar minerals and rocks which are partly of gel structure. This is specially noticeable in desert areas, and may often be directly observed in the morning hours when the sun suddenly heats stones which have cooled during the night. It is not impossible that here, in addition to the abrupt variation in temperature, dehydration of the surface layers plays a part in setting up severe strains.

The extent of temperature weathering in dry areas is enormous, as is shown by the gradual reduction of mountain crests to half their initial heights. These powerful effects are naturally limited to the surface, but with decreased intensity and as secular phenomena they undoubtedly extend downwards, as Lang rightly noted, as far as do variations of temperature. This depth is much deeper in the case of rock than it is with soil.

Soluble salts are an important factor in rock disintegration in all warm areas and have a specially marked effect in all hot and dry climates. The influence of salts on weathering, which Schweinfurth, Walther and others actually regard as the chief factor of weathering in desert climates, has been described as cleavage by salt. Walther, who has made a special study of the laws of desert formation,



RUPTURE OF ROCK MASSES
(Granite hill partly flooded by the Assuan Dam, Egypt)

expresses himself as follows: "During the night the hygroscopic salt absorbs minute traces of water from the air and the salt solution then readily penetrates capillary crevices in the rock. When insolation begins the water evaporates and the salt crystallises out. There ensues an increase of volume, and as a result the capillaries are widened so that in the desert as soon as the sun strikes a rock face that was previously shaded one may readily observe an intense cracking and peeling of weak rocks." Elsewhere he expresses himself no less definitely as to the mechanism of cleavage by salt. "As salts separate from the rock there are formed granular and fibrous crystals which by crystallisation in all directions must have the same effect as the freezing of water has in our climate; salt thus not only weakens desert rocks by chemical action but also breaks them down mechanically."

There is no question of the correctness of the observations which form the basis of these remarks, nor of the very large part played by salts in rock weathering in hot and dry climates, and indeed to some extent in the humid tropics also. One meets with the phenomenon at every turn. On the other hand, we may doubt whether the splitting of rocks results from pressures set up by the crystallisation of salts. Cleavage by frost seems an obvious analogy but is not in fact at all similar. Freezing water splits rock because when the temperature falls below zero the volume of water contained in a crack suddenly solidifies as a whole and expands as a whole. It is necessary also that the mouth of the crack should be closed by ice or otherwise in order that pressure should develop at all. In default of this, water will escape as it expands in the moment of freezing. In the case of crystallisation, however, there is no question of an increase of volume when one compares the crystals with the solution that previously

occupied the crevice. As Walther himself notes, water evaporates prior to the commencement of crystallisation, and the volume necessarily falls and reaches a minimum when the crystals appear. Furthermore, crystallisation takes place relatively slowly, so that there is time for the crystals to exude into the ample space which is available. There is accordingly no trace of a sudden increase of pressure as is implied in the idea of cleavage by salt, but only a chance resemblance and the parallel with cleavage by frost is completely wrong.

The widening of cracks in which salts are present in turn as crystals and solution is a simple consequence of the specially intense action of such concentrated solutions on the wall material; this and all cases in which rock is reduced to fragments by salt is a chemical and not a physical process. Even the peeling and cracking of rock fragments, which is often very strikingly evident as salts dry out beneath the rays of the sun, has nothing to do with mechanical splitting. The salts crystallise, as usual, in single individuals which are but loosely connected. The cohesion of such a layer of salt is much less than that of the water film in which the salts were previously dissolved. When a flake of rock has been sufficiently loosened from the main body by chemical weathering it must then crack and peel because the force securing it to the rock mass is diminished. Undoubtedly quite large masses of rock are detached from steep walls in a manner suggesting a violent rupture, but this is due not to some new force but simply to gravity, wind and so forth, which obtain a better hold on the loosened fragment of rock.

Mechanical cleavage in the true sense can, however, occur to a small extent when rock components take up water or are oxidised. It is not known whether this is ever of practical importance.

One very active factor in wearing down rock in desert or steppe areas is wind-blown sand. That large masses of rock are thus pulverised, often in an astonishingly short time, is shown by the wide distribution of mushroom-shaped rocks. Walls of rock are at first hollowed out along the softest strata by the wind blast, which then causes extensive falls of stone, as may be generally observed in arid districts which alone provide the conditions for the occurrence of wind-blown sand.

In conclusion, plant roots growing in crevices exert a strong ruptive force. Instances of this are, however, always dependent on some special chance, and the effect can therefore hardly be regarded as of general importance in soil formation. On a small scale the same process attacks fragments of minerals and rock present in the soil and may here contribute somewhat to the further diminution of soil material.

The animal world has practically no share in the processes of physical weathering.

(*b*) *Chemical Weathering of Rocks*

There is hardly any other branch of science which has been studied from so many aspects and by workers of such diverse interests as the subject of the chemical weathering of rocks. Geologists and pedologists were, of course, interested in these phenomena which include the major processes of soil formation in general. Chemists and colloid chemists were largely attracted to these complicated changes which constitute Nature's biggest chemical experiment and involve reactions of more far-reaching practical importance than any other on the face of the globe. On the other hand, the complexity of the concept "chemical weathering" is such that no other subject has evoked such

diversity of theories as to the mechanism of these changes.

Even now there is complete agreement only on one point: "The single factor essential to chemical weathering is liquid water derived from the air; in absence of this all other agents are impotent" (Behrend and Berg). This pronouncement is, however, in the last resort the same as the old axiom *Corpora non agunt, nisi fluida,* and is too wide a generalisation to reveal anything as to the details of what is comprised under chemical weathering.

The chief property of water lies in its solvent action. Solution in a strict sense, that is, solution unaccompanied by change of material, is, however, only exceptionally of importance in soil formation, for very few rocks and minerals are truly soluble. If we exclude alkali salts, which can hardly be regarded as soil-forming substances, and also gypsum, of which the same is in a measure true, we are left only with the sparingly soluble carbonate rocks: limestone, magnesite and dolomite. Their solubilities in pure water are: Calcium carbonate, 1·31 mg. per 100 g. water at 16° C., magnesium carbonate 97 mg., while the mixed rock, dolomite, is still less soluble, as might indeed be inferred from the law of solubility products. In spite of these low solubilities carbonate rocks seem in nature to weather very easily, for deeply eroded hill-sides, pits and karst country indicate their susceptibility to atmospheric attack, while lime and magnesia are under natural conditions more readily washed away in solution than any other substance. The reason for this, however, is that atmospheric water, as has already been noted, is by no means pure water. Together with nitrates, oxides of nitrogen, ammonia and ozone, rain often contains hydrogen peroxide and, if near the sea, chlorides also. Gases dissolved from the air are also present, and the chief constituent is car-

bonic acid. Now carbonic acid reacts strongly with carbonates of the alkaline earths according to the equation,

$$CaCO_3 + CO_2 + H_2O \rightleftarrows Ca(HCO_3)_2,$$

which represents the formation of bicarbonate. Bicarbonate which results from this reaction is comparatively freely soluble; it is at any rate much more soluble than the original compound.

It thus appears that even with the carbonates of calcium and magnesium, which alone have to be considered in this connection, we have no genuine case of weathering by solution. Water, or rather the very dilute solution of salts and acids which constitutes rain, acts on these carbonates only after changing them. In this case also there is no exact correspondence between *Fracht* and *Frachtrest*, that is, between material carried away by the solution inducing weathering and material left behind, although when the reaction is reversed the original materials are more or less reproduced as solids precipitated either beside or at some distance from the place of solution.

The definition stated above, that chemical weathering involves rock components in a change which is in equilibrium with local conditions, holds also for the apparent exception of carbonate rocks in which the change seems to be simply a process of solution.

The only soil constituents to undergo a simple change similar to that of the carbonates are ferrous iron compounds, which were mentioned above as being the Achilles heel of a number of minerals in the tropics, and also iron sulphide. Ferrous compounds of iron when acted on by oxygen, oxides of nitrogen, hydrogen peroxide and ozone dissolved in water are converted initially into colloidal iron hydroxide, which for the most part separates out

near by in the gel form, and a residue of silicate. Sulphides, however, are oxidised to sulphates from which iron hydroxide and free sulphuric acid, a further important factor in chemical weathering, are commonly produced by hydrolysis.

The extent of these reactions depends, of course, on the amount of available water and the time during which it is in contact with the soil material and can react with it. When water is present in small amount and for a short time only, oxidation takes place with long interruptions and requires correspondingly long periods to reach completion. It thus happens that in arid districts, and quite generally where the soil climate is arid, that light to gray colours predominate in the soil unless the rock is very rich in ferrous compounds; red sands occur, of course, as in the deserts. Pale yellow and brown extend throughout. With larger quantities of water, longer reaction time and adequate aeration, oxidation proceeds rapidly. Brilliant red on rocks rich in iron, all shades of yellow and brown in substrata containing little iron, are thus the characteristic colours of the tropical and subtropical belt, except where organic substances share in soil formation and contribute other shades of colour to the surface and to adjacent layers of soil. With excess of water and consequent exclusion of air, as occurs in depressions or in plains with feebly permeable soil material, oxidation is held up and may even be reversed under the influence of organic matter. Compounds of ferric iron are then reduced again and the soil loses its bright colours.

All alumino-silicates, constituting by far the greater part of all mineral soil-forming substances, are naturally not affected by the atmospheric processes we have so far considered, since they are neither oxidisable nor soluble by simple conversion into acid carbonate. Until recently the view put

forward by Ramann was generally held to the effect that chemical decomposition of silicates originates in hydrolysis by hydrogen and hydroxide ions furnished in small amount by dissociation of water. In this scheme major importance was attached to the hydroxide ion since hydroxides of sodium, potassium, calcium and magnesium are almost always obtained when rocks and minerals are treated with pure water. Recent investigations on base exchange at electrically polar surfaces lead, however, to a fundamental revision of ideas as to the mechanism of silicate decomposition. It is certainly the case that when silicates are treated with water, especially at high temperatures such as rule in the soil of the tropics and subtropics, there ensues a vigorous hydrolysis. Hydroxides of the bases split off and aluminium hydroxide, iron hydroxide and silicic acid, together with residual clay, remain either as separate colloids or in a state of partial combination. The real agent in this process is not, however, the hydroxyl ion, as Ramann supposes, but the hydrogen ion, which displaces all other cations from the space lattice of crystals lying at the surface of the mineral particles. An alumino-silicic acid is next formed, and, finally, by further splitting off of the aluminium in the form of colloidal aluminium hydroxide, the weakly dissociated silicic acid is produced. The displaced bases are found in the weathering solution as hydroxides and also as salts of the anions contained in the solution: sulphuric acid, hydrochloric acid, nitric acid and, above all, carbonic acid. The chief part of the active hydrogen ion is derived not from hydrolysis but by dissociation of acids contained in the water, and of these the most important is carbonic acid.

With tropical and subtropical temperatures there is thus produced, as the first product of chemical weathering and as the starting material for the real

process of soil formation, a system of which all members are in equilibrium, and which includes the following constituents:

1. In the weathering solution as potential *Fracht* or cargo:
   (*a*) Hydroxides, carbonates (largely split by hydrolysis), chlorides, silicates, aluminates, nitrates and sulphates of the alkalies and alkaline earths.
   (*b*) Traces of colloidally dispersed sesquioxides and probably silica.

   The weathering solution has a pronounced alkaline reaction.

2. As potential *Frachtrest* or residue of non-transported material:
   (*a*) Unchanged material and siallitic residues of the minerals. These residues include, in the case of alkali felspars, crystalline kaolin, soluble in sulphuric acid, and in the case of calcium sodium felspars, allophane in the gel form. The latter is perhaps produced in part by rapid precipitation from the weathering solution.
   (*b*) Allitic material: aluminium hydroxide either crystalline or in the gel form, and iron hydroxide in the gel form.

According to Harrassowitsch group (*b*) is wholly formed by rapid precipitation from the weathering solution.

The extent to which the different components occur and the nature of the equilibrium established depend chiefly on the mineralogical composition of the rock. The intensity of decomposition is determined not by the character of the rock, but principally by the amount of water available and the length of time during which it

acts. Where the amount of water is small and the period of action is short, as is the case in arid and semi-arid districts, siallitic and allitic bodies are formed in small amount; in other words, there is very little production of any kind of clay material, clay here being used in the sense of finely divided material. For this reason all arid or semi-arid eluvial soils are sandy, or at least light soils low in colloidal substances. Where there is more water and the period of action is longer, even solid rock may be completely decomposed to a great depth, as in the decomposition zones of soils of the humid tropics. These often consist almost entirely of colloidally dispersed material and resemble typical heavy soils.

Owing to the complexity of its composition, the system thus formed as the first product of chemical weathering is the reverse of stable. Each movement of the weathering solution leads to movement of its cargo either upwards or downwards, as determined by local conditions of air climate and soil climate. Where the climate is intermittently moist the direction of movement is, as a rule, periodically reversed. This movement involves a displacement of equilibrium in a determined direction, and this notably affects the character of the soil to be formed. A still greater displacement of equilibrium is occasioned by a downward movement of the water stream carrying organic matter with an acid reaction. When organic matter predominates in the weathering solution there follows a removal of bases and partial removal of sesquioxides, whereas only small amounts of silicic acid are carried down. Typical siallites are so formed. If owing to lack of organic substances the solution is weakly alkaline or neutral, silicic acid is removed and all compounds of silica and the sesquioxides are often completely dissolved. Bases and silicic acid are carried off and typical allites result. These extreme types of

soil formation are, of course, less common than intermediate formations, allitic siallites or siallitic allites, which cover the greater part of the humid and semi-humid tropics and subtropics.

Although the primary process of weathering is uniform, the final character of the soil formed is thus influenced by local conditions of moisture and by the acid or alkaline reaction of the system, which chiefly depends on the amount of organic matter brought in and the nature of its decomposition. This holds in particular for the upper layers of soil in so far as they are liable to infiltration by acid or other substances. At greater depths in the soil up to a point at which unchanged rock occurs, decomposition on the whole maintains its primary character. This is to be seen only in soils formed *in situ* in humid climates, since in arid climates, owing to lack of moisture, soils formed *in situ* are of insufficient depth.

To what extent animal life has a direct share in chemical weathering is a question which has as yet been very little investigated.

Evolution of carbon dioxide, accompanied perhaps by organic acids, by plant roots, mobilises the hydrogen ion which displaces bases, calcium, potassium, etc., from combination in the colloidal complexes of the soil. By this means these bases, in addition to those occurring as salts in the solution which is in equilibrium with the complexes, become available for the plants. This involves a displacement of the equilibrium existing in the soil system towards the acid side, that is, in the direction of siallitic weathering, for the soil is thereby slowly denuded of its basic substances. Although this effect is no doubt quite general, it is not perhaps under natural conditions of very far-reaching importance for pedology even where plant production is very great.

Very little is known about the part played by micro-organisms in the weathering of rocks in the tropics. It seems clear, however, that there are no "laterite bacteria".

In temperate climates the activity of the lower plants as first pioneers of life has unquestionably a considerable effect in the early stages of rock weathering. They are to be found in the tropics also, but their distribution is greatly restricted by intense surface heating due to insolation. When there is a layer sufficiently thick and loose to prevent big variations in temperature and moisture, there generally is a flora of lower organisms which presumably produce the same effects as in temperate climates. Unfortunately investigations on this point have not yet passed a very elementary stage except in the case of some species of particular practical interest. Study of tropical soils gives the impression that the number of varieties of microflora is at least not greater, and often probably less, than in cooler parts of the earth. This refers more particularly to soils of dry areas: in them the topmost layers of soil are often almost sterile.

Except for quite local influences there is only one group of the animal world which has to be considered as an important agent in chemical weathering. This group includes the termites and ants, the latter being of minor importance. Termites, which belong to the family of the neuroptera, and are incorrectly called "white ants" in hot countries, influence the decomposition of soil material in two ways. In building their nests, which are often several yards high and cover a wide area, they expose large quantities of soil material to the air and thereby greatly promote its oxidation. It is certainly the case that these nests provide striking evidence of the fact that many gray earths of the tropics and also many yellow earths are not special

climatic formations, but are either derivatives or forerunners of normal red earths. Thus in gray earth districts the termitaria are often oxidised to

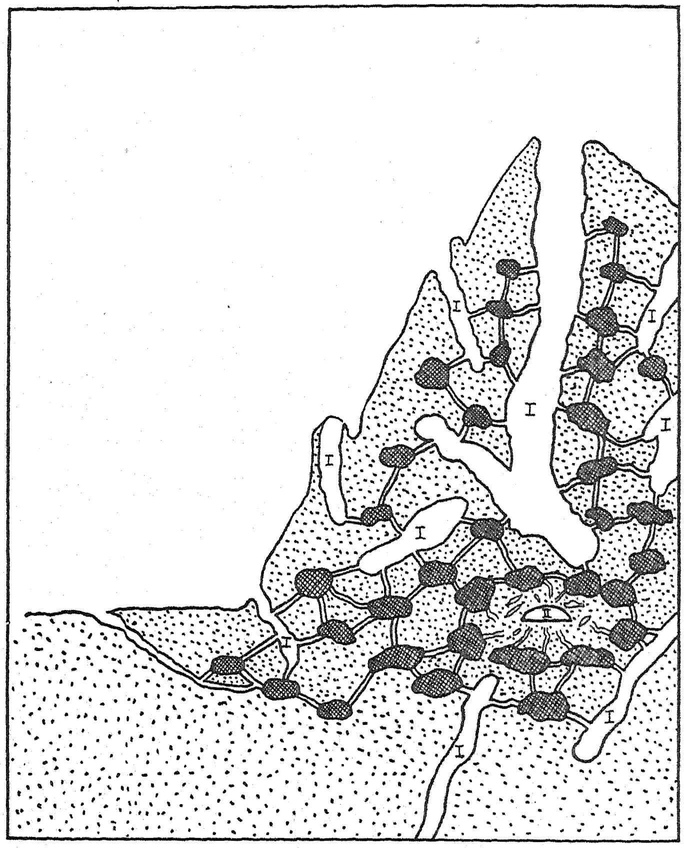


FIG. 12.—CROSS-SECTION OF A TERMITARIUM SHOWING I, AIR SHAFTS; II, CHAMBER OF THE QUEEN AND FUNGUS GARDENS.

a pronounced red. The usual assumption that in cases where termitaria show this colour the subsoil is red is almost always wrong. The red soil here results from the activity of the termites, which by promoting aeration make possible the generation

or regeneration of this stage from gray or yellow earths.

In very many districts, and particularly in the gray earth district of Africa, native cultivation is very noticeably restricted to red-earth areas rich in termitaria, and indeed the broken-down nests are also used in spite of the danger that termites will attack the crop. The reason for this choice lies in the physical properties of the red earths, which make them attractive to the natives, and also in the fact that these termite-infested red earths are for the most part considerably richer in plant foods than the surrounding gray soil. This is readily verified by analysis and is a consequence of the habits of the termites, and especially of their fungus gardens, which enrich the soil. In the Indies this special composition of termitaria has been exploited on a large scale and, in some cases, with striking success.

Ants have an influence similar to that of the termites, but of much less importance.

The indirect effect of the animal world on the chemical weathering of rock and on the course of soil formation is of much greater importance than the direct. This indirect effect involves organic debris of all kinds. The way in which this is changed to humus will now be considered.

(2) The Conversion of Organic Residues in the Soil into Humus and the Influence of this Process on Chemical Weathering

Attention has already been drawn to the fact that views on the nature of humus substances are in general still obscure, and that hardly any investigations have been carried out on humus forms of hot climates. These humus forms are in many ways of a peculiar kind. If as a compromise

we take the view that humus consists of a mixture of well-known simple chemical substances, together with special products of high molecular weight which are formed by decomposition of organic matter, we shall, in spite of this diversity of opinion, be able to form a fairly reliable outline of the processes which affect plant materials falling on to the soil.

In the hot regions of the globe the soil fauna is much more active than in temperate climates in reducing dead organic material to minute fragments, whether trees, many cubic yards in volume, or the finest leaves, and this activity increases with increase of rain and of vegetation. By far the most important agents in this respect are the termites and ants. One can hardly form a just idea of the importance of this mechanical subdivision from the pedological standpoint without having witnessed the prodigious exploits of these little creatures. In books of travel one finds romantic accounts of "overthrown giants of the forest blocking the way" or "making the forest almost impassable". The tropical forest, like any other untended forest, certainly contains quite a number of fallen trunks, but they are in fact very impermanent features. If one examines the fate of such a trunk one soon finds that its existence covers only a few years as a rule, or an even shorter time, unless it happens to be a specially hard kind of wood. Although the log seems to be intact it is soon riddled by termite passages, and within two years at most even the biggest tree trunk is no more than a system of corridors. The bark remains untouched but encloses only cavities, for the inside has been converted into dwelling-places for ants or termites, or perhaps for both. At last the outer shell, meticulously preserved by the termites, which, owing to the softness of their skin, need it as protection against evaporation, breaks under the weight of

epiphytic growths, and a few months later the only trace of the former obstacle is, in inhabited regions, a new twist in the track. The detour seems meaningless unless one knows its origin, and is preserved by the conservatism, and indeed by the good judgment, of the natives. For when the feet are bare it is by no means pleasant to hack a new path through thick wood, and one can readily understand why the natives stick to their devious routes. The well-known snake-like windings of native tracks are to some extent an expression of their conservative tastes, but they are not foolish as the European often supposes. One may feel sure that in tropical forest or heavy bush every apparently meaningless deviation corresponds to the fall of a tree at some earlier time, and by taking this as a statistic one may gain some idea as to the growth and decay of the forest.

The small creatures of the forest not only chop up organic debris of all kinds from tree trunks to leaves, but also use it as their chief food and subsequently excrete it. In this way the animal world not only prepares the way for vegetable organisms which are chiefly responsible for the final decomposition of organic material, but actually enters into keen competition with them. This is the case even in quite arid steppe lands, where, if one's interest is aroused, one may clearly trace the extensive destruction of organic residues by ants and termites. The remarkably slow formation of humus in the tropics and in many parts of the subtropics may be largely ascribed to the activity of smaller members of the animal kingdom, which withdraw from humus-forming agencies a very large part of the necessary starting material.

On the practical side this activity of the animal world is much used by natives in clearing land. They content themselves, as a rule, with cutting the larger trees rather high above the ground or simply

burning them down, and then confidently leave the further clearing of the land to the termites and ants which at once take up their task. It must be added that they claim payment for their work, when the fields are ready, by attacking the crop.

Residues of insect activity and of the insects themselves must form a considerable part of humus substances in the tropics. They have, however, nothing to do with humus in the narrow sense, that is, with humus formed by decomposition of residues through vegetable micro-organisms.

A great part of this humus consists of the dead remains of bacteria, actinomycetes and fungi. In particular, it seems that the chief part of soil nitrogen is stored in these remains and is there in a form which is not easily available. We have here to deal not only with bacterial proteins, but with substances resembling chitin, which are widely distributed in animals as well as in plants, and are distinguished by their high resistance to decomposition and by their high content of nitrogen. As would be expected, the major part of humus consists of material formed from high molecular organic substances which are contained in plant and animal remains.

Proteins which are characterised by their content of nitrogen, phosphoric acid and sulphur are, with very few exceptions, readily attacked by microflora. They rapidly break up into more simple substances either by decomposition in presence of air or by even more rapid decay when air is excluded. In the former case aerobic bacteria are at work, and of these *Bacterium vulgare* and the Proteus group seem the most common in the tropics as elsewhere; in the latter case the anaerobic Clostridium species play a major part, as may be seen from any preparation of tropical soil. The products of decomposition are for the most part acidic, since

some ammonia is split off from the decomposing molecule of protein. Thus acetic, succinic, propionic, caproic and other acids have been identified. Of particular importance from the pedological point of view is, as Blanck rightly emphasises, the liberation of sulphuric acid. Amines and other nitrogeneous substances of simpler structure are produced at the same time.

Of plant materials which contain no nitrogen, all fats and resins, oils and waxes are very resistant to decomposition, as is also lecithin, which is to be found almost unchanged in humus. It imparts striking properties to a kind of humus occurring extensively in dry hot districts where the cover consists of plants rich in resin and wax. Fallen leaves, for example, are largely mummified and only slowly undergo further decomposition.

Lignin affords a rather better foothold for soil micro-organisms. It occurs in the woody parts of plants. It probably serves only to a minor degree as a source of energy for the microflora. The amount present in soil does not therefore diminish very much, but its appearance and chemical behaviour are definitely changed. "Its solubility in alcohol increases, it becomes darker, the carbon content increases while the hydrogen content remains constant. There is a decrease in methoxy groups accompanied by a corresponding liberation of phenols whereby the lignin, originally neutral, acquires an acidic character and becomes soluble in alkali. In brief, lignin changes to humin" (K. Rehorst, "Decomposition of Organic Substances", *Bodenlehre*, vol. ii.).

It appears, therefore, that lignin is the source of humus carbon which is extremely widely distributed and which, particularly in semi-arid climates, makes up a very considerable part of the total humus materials in the surface soil. The dark colour of many tropical and subtropical gray earths is

correctly ascribed to their content of humin or humus charcoal, a circumstance which is easily intelligible in view of the resistant nature of lignin produced in large amount by the woody vegetation native to such areas.

Pectins are to be regarded as the material from which lignin is formed. They compose the greater part of all non-woody plant tissue and fall to the ground in large amount, and are there fairly quickly decomposed, although up to the present we still lack exact knowledge as to the special processes involved. Of its decomposition products tetragalactonic acid and its derivatives are fairly resistant, and probably form the chief part of the group of substances which Sven Oden calls humus acids. The humus acids, when precipitated from alkaline solution by addition of mineral acid, may be divided into two parts by treating the precipitate with alcohol. The insoluble residue is distinguished as humic acid, and the soluble group as hymetomelanic acid. In neither case does the material consist of a single chemical substance. The same is true of the water-soluble fulvic acid (Sven Oden), which also differs from humic acid and hymetomelanic acid by its greater strength as an acid and by its light colour.

As was noted above, the subsoil layers of tropical soils are exceptionally rich in light-coloured organic substances of a strongly acidic character, this being specially marked in heavy tropical forest. We may assume that under such conditions non-woody material, mainly pectin, is the chief starting material for humus formation. It is accordingly probable that further investigations will show that the acidic organic substances of the lower layers of heavy forest soil are for the most part comprised within the fulvic acid group.

Waksman's recent researches have clearly shown

that cellulose, which is present in all plants, is of great importance in soil as a source of energy and of material for micro-organisms. This importance is displayed only under aerobic conditions, that is, where air has good access to the soil. Under these conditions from 50 to 65 per cent of the carbon is completely burned to carbon dioxide, from 25 to 35 per cent is incorporated with nitrogen by the microflora and converted to cell material, while the residue remains as an intermediate product in the soil.

In temperate climates bacteria are the most active of micro-organisms in the decomposition of cellulose under aerobic conditions; Fungi and actinomycetes play a minor part. In the investigation of tropical humus soils, however, the reverse is found; actinomycetes are by far the most active agents. Their presence is often to be detected by the strong "earthy" smell of tropical humus. Moulds apparently take the second place, piercing the mass with their mycelia. Not till then can yeasts and bacteria obtain a footing. This reversal in the composition of the microflora must be partly due to the very strongly acidic reaction of all humus formations in tropical areas of heavy rainfall since the acidity is less favourable to development of the bacteria. The composition of the microflora in drier regions is not known.

What happens to cellulose under anaerobic conditions such as occur in the lower layers of soil and where the soil is waterlogged is at present a subject of scientific controversy. The older writers put forward a far-reaching and rapid decomposition with formation of methane, hydrogen and carbonic acid, followed by extensive denitrification under the influence of appropriate anaerobic bacteria. Waksman's studies seem strongly opposed to this view, as according to him decomposition of

cellulose occurs only to a small extent and the major part of it remains in the soil as an intermediate product. In view of the work of Bergius on artificial humification it may be assumed that the cellulose is eventually converted to humic acids. It seems questionable whether the Waksman-Bergius scheme applies to tropical conditions. Thus the meagre formation of humus in comparison with an enormous fall of leaf and other material affords a strong presumption that even under anaerobic conditions the decomposition of cellulose is intense, and the exceptionally vigorous evolution of methane which is to be seen in all swamps points in the same direction.

The soluble carbohydrates, acids and so forth of plant substances affect soil formation only in so far as they constitute an excellent food for microflora and are instantly consumed.

It is quite an open question as to how far denitrification processes are involved in the decomposition of organic substances under tropical and subtropical conditions.

The ratio of carbon to nitrogen (C/N ratio) in humus varies in the humid tropics from about 8 to 12 at the surface, sinking sometimes to 4 in the subsoil of very acid soils but reaching 15 to 16 at their surface. A general average based on all available figures is 10. In drier tropical and subtropical regions the mean seems to be rather higher; in the Sudan and Egypt, for example, it is about 12 or 12·5.

Special note should be made of the high phosphoric acid content of humus material in the tropics and subtropics. There is often more in the humus than in the whole mineral fraction of the soil. This phosphoric acid has the property, which has indeed been observed in other places, of being very sparingly soluble in acids but comparatively easily soluble in alkalies. It is supposed that this phos-

phoric acid is also readily available for plants, at any rate where the soil has an alkaline reaction. When analytical data are being considered it is accordingly of importance to know how the figures were obtained, for even with soils moderately rich in humus, as are very many soils of the humid tropics, figures for acid soluble phosphoric acid give an entirely false picture.

To summarise this discussion as to the decomposition of organic material, we may note that the most important result of this change is the production of organic acids of varied molecular size, together with free sulphuric acid. These organic "humic acids" in the widest sense are in part quite "strong". They are also in part readily soluble in water, and even the acids not soluble in water readily pass into colloidal dispersion. As their degree of dissociation is considerable, they not only neutralise bases produced by weathering in soil but also decompose carbonates and even split up neutral salts to some extent. Their hydrogen ions must of course have a powerful effect on the sorbtion complexes of the soil and also attack soil material which has not yet reached the colloidal stage. In this they are notably assisted by sulphuric acid.

Their great influence on the character of all soil formation will be discussed in connection with the production of the soil profile. Here our interest is confined to the part they play in the weathering of minerals and rocks. On solid rock the "humic acids" can only exceptionally exert any effect, since there the conditions necessary for their production, a vigorous vegetation, are naturally not satisfied. Where hollows in the rock permit a local accumulation of humus material, it has an enormous effect in dissolving and decomposing the rock. In such places the combined action of the acids forms, as Blanck has shown, deep holes which are often mis-

taken for pot-holes. In softer rock the process of disintegration spreads down cracks far into the centre of the mass. Where the rock material is broken up, as is the case in soil, it becomes bleached under the action of "humic acids", and there is some loss of bases and greater loss of alumina and iron, while silicic acid accumulates. The soil becomes podsolised. The long-held opinion that this produces not merely siallites in general but a quite special kaolin and kaolinite can no longer be maintained, as has been shown by recent investigations of Blanck, Harrassowitsch and others. The so-called sol-weathering by humus substances certainly leads to partial solution of felspars but not to their deep-seated decomposition, which is a necessary preliminary to the formation of kaolin, and which occurs only where the reaction in the zone of decomposition is alkaline.

(3) The Displacement and Redeposition of Soil Material

In treating of climatic factors at work in soil formation it was noted that frost, one of the most important agents in temperate regions, is completely absent from the tropics and subtropics. Absent also is ice, an agent in the displacement of soil material. This deficiency is more than made good by the intensified activity of the remaining factors which under tropical and subtropical conditions not only attain greater magnitude than in temperate climate but function in an exceptional way. Water and wind in conjunction with gravity are the prime agents in the displacement and bedding of soil wherever the configuration of the land affords scope for their activity.

The sudden influx of huge quantities of water which results from high density of rainfall even in

PLATE VII

Erosion of a Volcanic Mass

arid districts entails a very heavy flow of water, not only in all rivers and streams but also in actual or potential gullies. Extremely deep erosion is the consequence, especially when heavy rain follows a long dry period during which the uppermost layers of soil have been loosened by drying often to a considerable degree. On the large scale this is shown by the characteristic contour of whole mountains. (*See* Plate VII.) On a small scale this removal of material is shown by surface scouring or by the formation of gullies in all sloping soils, where every strong shower carries countless tons of soil material from the slopes into flats and valleys. Even with a moderate angle of slope heavy rains often produce extensive landslip and pronounced creeping, unless careful precautions against these occurrences have been taken in cultivation of the land by erection of strong terraces.

From the pedological point of view the result in all undulating country is usually marked shallowness of all sedentary soils formed on the upper slopes, together with the formation of colluvial soils at the foot of mountains and hills. The colluvial soils are very deep and generally have bulky rock fragments at the bottom. They are distinguished from sedentary and alluvial soils by their great variety of particle size, and they are often the most valuable soils of a district. Owing to favourable moisture conditions they usually carry, as has already been remarked, the most luxuriant vegetation of the region and are favourite sites for settlement of primitive agricultural peoples.

The fate of suspended solids carried in river water and of pebbles set in motion by the current depends of course on local conditions in each case, and also on the length of the period of high flood in the rivers and streams. With constantly flowing rivers the transport of pebbles is usually restricted

to the river-bed even if the flow of water at the hill-foot leads to extensive flooding of the more level country. Owing to sudden accumulation of water, floods of this kind, even from small rivers, may cover colossal areas, thousands of square kilometres in extent. The Karun of South Persia, for example, carries in the dry season only about 300 cubic metres of water per second, while its catchment area receives on the average only 300 mm. precipitation. The Karun nevertheless puts some 20,000 square kilometres under water each year. This is owing to the fact that at the time of high flood, which lasts only a few days or hours, about 5000 cubic metres per second pour down the river-bed. The enormous inundations of the Nile and Amazon, of the rivers of south China and of the Magdalene river, are well known.

These inundations, of course, carry huge masses of mud over the river-bank. As the speed with which water moves from the bank into the flooded area steadily falls off, its carrying capacity also decreases, and the larger suspended particles, often of a sandy character, settle near the river edge, forming embankments which are very typical of almost all streams in hot climates with heavy rainfall. These embankments are often many yards above the level of the surrounding country and form a ribbon of lighter soil along the stream. Since there is a specially good supply of subsoil water, they carry a thick cover of trees and bush. Corridor woods, which were mentioned earlier, are thus formed in drier areas which would otherwise support steppe vegetation only.

The finest suspended particles settle in depressions of the surrounding country, where the water eventually evaporates or sinks into the soil after perhaps lying there for weeks or months. The low-lying clay soils of the tropics are thus formed.

They are usually noticeably striated, and are so heavy as to be impossible of cultivation under temperate conditions, but nevertheless in the hot regions are often among the most fertile soils of the world. Their somewhat peculiar properties will be considered elsewhere.

It is evident that the bed level of every river or stream in the settling area must gradually rise. This is especially the case where the main flow consists of short flushes occurring at any rate once and sometimes many times in the year, but falling as quickly as they rise. This happens at the boundary of the dry zone, and there both river-bank and river-bed slowly but surely rise above the level of the surrounding plain and so present an easy means of irrigating the adjacent lands, provided that the initial flow of water is sufficient to give the necessary protection against accumulation of salt in the soil such as occurs in hot districts and that drainage is also possible. The reverse of the medal consists in a much intensified danger of flood when the river-bed has risen above a certain height. This can lead to the gravest catastrophes, as is shown by conditions in South China.

Quite peculiar conditions arise in dry lands where intermittent streams have practically a single period of high flood, and again in moister regions where there is a sudden change in the slope of the river-bed, as, for instance, where a river with a quick fall enters a plain at the foot of the mountains. Here the flood water piles up huge fans of debris, several yards high and spreading over a wide area far into the plain. The material composing the debris varies from rock boulders to the finest clay, owing to the irregularity of the flood. Water penetrates very readily in these fans, and in hot arid districts they are the places in which one may be sure of finding water below ground. In them also underground

water channels are constructed in countries where native irrigation has reached a high state of development, as in various parts of Asia and South America. These channels often run below ground for many miles and come to the surface near the edge of the fan, where the finest sediments and best soils are found. They are, then, the sole support of an intensive agriculture. In South Persia in the Jezd districts there are "kanates" of this kind more than 100 miles in length and tapping sources which lie more than 100 yards deep.

The transport and sedimentation of soil material in definite river-beds occurs on a much greater scale in the tropics and subtropics than in temperate regions, but there are no major peculiarities differing from what one would expect on the basis of experience in temperate parts. This, however, is not the case with sheet flow, which results from high density of rainfall. Sheet flow is certainly to be observed on a miniature scale in temperate climates, but its effect on soil formation is so slight as to escape notice. No appreciation of the significance of sheet flow is to be found in the literature, although there are occasional references to it. In spite of this, in all semi-arid and arid parts of the hot zones sheet flow is probably a most decisive factor in soil formation in all areas in which it can occur, that is, in all plains with so gentle a slope that definite watercourses are but rarely formed. Very light sandy soils do not permit sheet flow, but soils in which it does occur probably amount to well over half the total tropical and subtropical country.

Whereas a quite appreciable slope is necessary for the production of watercourses and for the occurrence of erosion as commonly understood, since water has no erosive action until it acquires a certain kinetic energy, the most minute slope is sufficient to engender sheet flow. Slopes which are

only a small fraction of a degree set up sheet flow under heavy rainfall. Such conditions extending over enormous areas are, however, precisely the distinguishing feature of the gigantic plains of the tropics and subtropics in all continents. In such plains the area of "slope" very much exceeds the area of "hollow", and accordingly the water, instead of moving along definite channels, covers the whole land in a sheet and concentrates in the low-lying parts. Its motion may be scarcely perceptible, but nevertheless colossal amounts of water and of soil material are thus accumulated. The erosive action of sheet flow is small, owing to the slowness of flow, and is usually practically nil. The soil material is, however, previously prepared for transportation, and the sheet of water has merely to move it along. It consists in the main of all loose plant debris lying on the surface. This may be seen by simple inspection of sheet flow. In the second place, loose dust and particles of clay are also removed from the soil surface. Last, but not least, sheet flow also transports very fine particles of soil material which are dislodged from the surface by the impact of the raindrops. If one watches sheet flow attentively one sees that each heavy drop of rain raises a spurt of muddy water so that within a short time the whole sheet of water is turbid and a large amount of material is carried in suspension. As the movement of the water is exceptionally steady, these very fine particles, together with material of low specific gravity, may be carried for great distances. The larger particles, of course, settle at once.

By this means even the smallest depression that can hardly be detected by the eye is in the course of time slowly but surely filled up by sheet flow. No catastrophes of the ice ages have interrupted the process, and, accordingly, development through thousands of years has produced in the tropics and

subtropics the very characteristic clay flats which cover great stretches of land. They differ from alluvial clays, as ordinarily understood, by their lack of striation, which arises from the fact that successive increments were so minute that it is practically impossible to detect the individual layers. These clay flats are to be regarded as the final result of sedimentation from sheet flow. Their precursors, which may almost always be traced below the clay, are the infiltration soils of shallow depressions. These are particularly noticeable in tropical Africa, where they consist of a vast and relatively coarse bottom layer. When such soils are examined in respect to particle size the occurrence of well-marked maxima in coarse sand and clay leaves no doubt as to the manner of their formation even if local conditions be omitted from consideration.

Owing to the inclusion of large amounts of reducing organic substances, all the sediments derived from sheet flow are, as one would expect, gray or black soils ranging from clayey sand and sandy clay to heaviest clay and showing to a great depth a low and fairly constant content of humus.

On exceptionally light soils, and particularly in regions of granular rock, such as sandstone and granite, sheet flow commonly sinks into the soil without reaching the hollows themselves. In this case clay (of which there is but little, since the original material contains practically none), together with notably larger amounts of organic matter, are deposited on the slopes. Deposits of quite considerable extent may thus be formed in the middle of relatively sandy areas, and there constitute more or less clayey humus soils which are for the most part very shallow.

The residual soils which slowly form in the wake of the sheet flow are almost invariably distinguished

by a typical skin of sand, a surface layer ranging from a fraction of an inch to, at most, one or two inches in thickness. Where the original soil is a clay, as may often be seen in Sumatra for example, the film of sand has, on superficial inspection, often led to quite erroneous judgments as to the value of the soil. Sheet flow is unable to carry sand grains, and they must therefore accumulate at the surface of the original soil and so form a thin layer that completely cloaks the character of the soil immediately below it. In such areas careful inspection of the subsoil is imperative.

The sand layer lies on the soil like a pavement in miniature, and is an exact analogue of the pavements which are formed on a much larger scale by action of wind in all arid or semi-arid parts of the hot zones. There wind exerts its full power in forming or transforming soil, whereas in the region hitherto under consideration its action is inhibited by a greater degree of moisture and by denser vegetation. The power of wind to lift and transport soil material depends chiefly on its speed, just as is the case with water. The accompanying diagram (Fig. 13) shows the size of particle transported at different wind speeds. Particle diameters in millimetres are given as a function of wind speed in metres per second, the figures being based on what observations and calculations are available. The curve represents the equation

$$y = 0{\cdot}0268x^{1{\cdot}568},$$

where y is particle diameter in millimetres and x the wind speed in metres per second. It is at once evident from the diagram and equation that even moderate storms of fifteen to twenty metres per second can transport quite large particles. The extent of transport is increased in so far as wind speed increases appreciably with increasing distance

above the obstructions of the soil surface. Averages calculated from a long series of observations show close agreement between observed data and figures derived from the equation given above. Individual values, of course, vary between wide limits, since

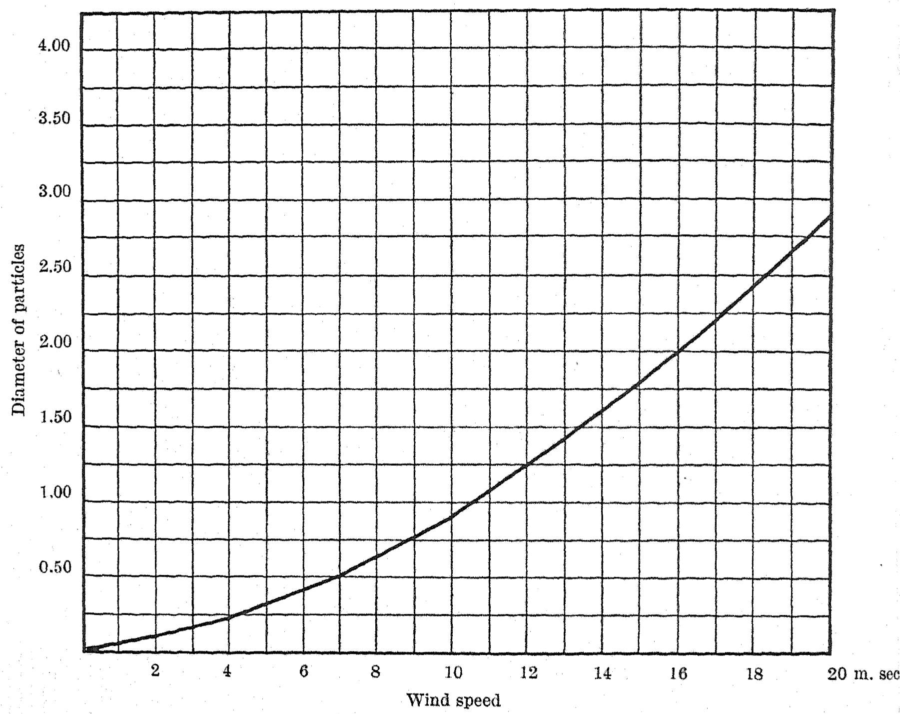


FIG. 13.—RELATION BETWEEN WIND SPEED AND SIZE OF TRANSPORTED PARTICLES.

the specific gravity and shape of the particles must have a strong effect. A further major cause of variation lies in the fact that the wind speed to be measured is itself a mean value which defies calculation owing to eddies always present near ground-level. It should be noted that in all eddies the local wind speed far exceeds the average, and that quite strong suction is often set up at the centre of an

eddy. Eddies have thus an important share in transporting and loosening soil material when the wind is a direct one. They have a far greater effect on the course of events in definitely cyclonic winds which result from uneven heating of soil and air and are often very violent. Their true domain is the bare or almost bare region of semi-arid or arid climates. In the dry steppe and desert local eddies begin to form a few hours after sunrise. At first hardly noticeable, they rapidly increase in size until at midday the "dust devils", as the Arabs fancifully name the ascending spirals, sweep through the land often in graceful columns hundreds of yards in height. Not until late in the afternoon does the phenomenon cease.

The speed of air within the spouts, both vertical and horizontal, far exceeds that of the strongest direct hurricane. Even in a small cyclone roofs are torn from buildings and trees broken. In tornadoes huge trees snap like matches, so that one may trace the path of such a cyclone many years after its passage by evidence of devastation. Their destructive action on loose dry soils is correspondingly strong. The whirling columns raise large amounts of loose material, chiefly fine sand, dust and organic debris, which may then be carried for long distances by the direct wind.

The whole soil surface is denuded. Only the larger particles remain and form the pavement already mentioned, which may vary from a film of sand to a pavement of stones, as determined by the material present in the soil and by the violence of the linear or cyclonic winds of the area. The original soil lies below this pavement and usually at a shallow depth, since the crust naturally affords good protection against further erosion. In this way enormous expanses of stone lands are formed. The Arabs call them *hamada* or *serir*, according as

the stones are angular or rounded. This is the origin also of the stony stretches derived from colluvial soils of widely varying particle size and found in dry districts at the foot of practically every mountain. It is well known to natives of the dry lands that at a short depth below such expanses of stone quite good, though stony, cultivable soil may be found, and areas of this sort are in fact often cultivated.

The distance to which wind carries material depends on the circumstances of each case. Coarse sand is not raised to great heights, except in actual cyclones, and rapidly settles again in the typical wandering sand deposits. These wandering sand dunes are of importance to agriculture only in that they may endanger or destroy wide stretches of cultivable land in dry countries. Mesopotamia and South Persia provide striking examples of this. Extensive and almost level plains of sand may also be formed, and these are sometimes of considerable agricultural value where water is available. Dust is carried for enormous distances, since even weak linear winds are sufficient for this. For the same reason dust storms carry dust and fine sand to great heights above the ground. In Persia, for example, it was impossible to fly over a dust storm of no particular severity, since even at 5000 feet elevation the dust was so thick that not only was there no possibility of orientation, but one lost all appreciation of the relation of the machine to the horizon. The enormous thickness of many aeolian formations shows what huge quantities of soil material are carried by wind where the climate is suitable. These deposits would be even deeper were it not for the protective action of the sandy or stony residue which forms in dry districts. Further resistance to erosion by wind is offered by cementation of the soil crust, unless this is broken up by wild or tended herds or by other animal agency. Vegetation has a

still stronger protective effect. It not only reduces wind speed, and so hinders the removal of material, but also greatly promotes the settling of dust and sand which have often been carried by the wind from immediately adjacent areas bare of vegetation. Where vegetation is sparse the so-called capstan lands, in which each bush stands on its own little hummock, are thus formed. With a closer growth of vegetation, however, if dust-laden winds penetrate the area they deposit their dust slowly and evenly, especially when the vegetation is moist, and the deposit remains where it settles. If calm or rain occurs when the air is charged with dust, the deposit at the edge of the larger dry steppes and deserts amounts to many tons per acre. In the course of a few decades quantities such as these are easily noticeable as deposits all over the soil, especially as the dust contains organic matter in sufficient amount to be of importance in soil formation. As the surface layers of the dry areas from which the dust came are for the most part enriched in bases, and notably in calcium, there is also an important introduction of basic material.

As the proportion of dust carried in increases, the soils, at any rate in their upper layers, are gradually converted into aeolian mixed soils. Slowly and, in individual cases, imperceptibly the layer of dust steadily grows higher in areas of dust-fall, and the vegetation conforms to the changed conditions by increased growth as the plants root freely in the rich deposit. The deeper parts of the root system die off and, as was noted above, become the starting-points for calcium carbonate concretions. This building up of the soil may continue for thousands of years, until there is formed from the aeolian mixed soil a true loess or wind-borne soil which shows no striation and is impregnated with a calcified network of roots and of cornstones (*Lösskindchen*). In some dis-

tricts loess is often hundreds of yards in thickness, and the process of formation may still be readily observed in the torrid zones wherever incidence of rainfall is propitious. The normal colour of loess is light yellow to brown, corresponding to the colour of the soil of the steppe areas from which the material originated. Oxidation promoted by thorough contact with air tends to increase the yellow shades. In the neighbourhood of wind-eroded red-earth districts the dust naturally has a red colour and the aeolian soils are accordingly red also.

In contrast to sedimentation from water, deposition of dust from the air is limited by no topographical influences but is determined by vegetation. The effect of vegetation is greater as the plants are bigger and more moist, since moistened dust is held very securely and is so protected from further wind action. Blankets of loess thus extend rather irregularly, as in Mexico, where they reach the upper limit of tree growth and spread beyond that up the mountain-side.

Dust falling on to pools of water is of course sedimented there. In this way many lakes of desert areas are gradually filled up. Lake loess so formed naturally does not show the structure characteristic of wind loess: calcified roots are absent and there is often well-marked bedding. It resembles wind loess, however, in mechanical composition, which is determined by wind transport, and consists almost exclusively of fine sand and dust or clay, while particles exceeding 0·25 mm. in diameter are either absent or present only in very small amount.

As all loess soils form a material which is very readily transported by water, *Schwemmlöss*, *i.e.* loess transported by water, is a soil type which is widely distributed throughout the world and occurs in deep beds. This needs no further emphasis, as it follows from what has already been said.

Whereas loess formation or, more generally, the transport by wind of material derived from soil is a continuous process which produces substantial results only after long periods of time, the transport of volcanic ashes and dust is only made possible by the eruption of volcanoes. This is accordingly episodic and can achieve very considerable results in a short time. Careful investigations in the East Indies have shown that material thrown up from volcanoes falls to earth in an ellipse of which the major axis coincides with the predominant wind direction. In the immediate vicinity of the volcano only the larger particles fall, often forming beds of great depth. Layers of ash some inches in thickness are, however, to be found up to fifty miles from the volcano, or even farther when conditions are specially favourable. Formation of soil which shows well-marked bedding therefore occurs on a large scale only in the neighbourhood of the volcano, but throughout the region of deposition the soil is often rejuvenated by addition of fresh unweathered material to a degree which is of real agricultural importance. The origin of this "natural artificial manuring", to use the jocular phrase of the Dutch East Indies, where these occurrences are common, can as a rule be ascertained with certainty by mineralogical analyses of the soil, since each volcano has its typical magma.

When the clouds of ash thrown up during eruption of a volcano reach a great height, they may float over continents before finally being brought to earth by rain or other cause. This is the explanation of volcanic dust soils and tuff layers which appear where there is no volcano in the whole neighbourhood.

Finally it should be noted that wind carries not only sand and organic and inorganic dust, but also micro-organisms and their spores and embryos.

These are consequently distributed all over the world. On the whole, therefore, the importance of wind as an agent in transporting and building soil is even greater in the tropics and subtropics than that of water, for the action of the latter is always determined by specific topographical conditions, and is not at work everywhere as is the wind.

(4) Soils of the Constantly Moist Tropics and Subtropics

The term soil profile is often used both in theoretical and in practical discussions, and its connotation seems to be free from ambiguity. Profile is the spacial arrangement of soil layers discriminated by macroscopic examination of a vertical section of soil. Nevertheless, if ever there was a case in which lack of precise definition of an expression which seemed too simple to need one has lead to confusion of ideas in science, it is certainly so with the term soil profile. The soil profile is, beyond doubt, the set of superimposed layers within a soil. The layers, however, have a twofold origin, and it is neglect of this consideration that has often lead to vagueness as to the meaning of soil profile. The layers of a soil are beds and horizons.

A bed (*Bodenschicht*) in this sense is an indication of the way in which the soil was formed and has no reference to the properties of the layer. Thus where rock or rock debris weathers *in situ* without producing a sharp demarcation between unchanged rock and soil one speaks of unbedded soil (*ungeschichteter Boden*). The expression is not a happy one, for here the weathered layer is the only bed present. In bedded soils, on the other hand, the several layers are often very clearly distinguished and reveal the conditions under which the soil was formed. In this case the bed is the product of a

discrete stage of growth in the soil. Thus volcanic ashes and sands may be superimposed in alternate layers as the product of a succession of eruptions. In soils which have been transported by water very definite bedding may be observed corresponding to deposition of soil material by successive increments. In this case there is usually a vertical gradation of particle size within the single bed. At the bottom the larger particles are to be found, and correspond to the increased carrying power of the water at the time of high flood. The particles become smaller and smaller towards the top of the bed, and fine material also fills up crevices below by infiltration. Beds of this nature commonly range from some inches to a yard in thickness, especially when the deposition occurs in standing water and extends over a long period of time. An interlocking of the single beds often occurs, especially in aeolian soils and in fan-like deposits from rivers, and sometimes amounts to pronounced cross-bedding.

If the amounts of material successively introduced are small, and if the single settling periods are short, the thickness of the beds naturally decreases. The soils, of which the low-lying clays of the hot zone are an example, then show bedding on a minute scale, so that microscopic examination makes possible a precise estimate of the age of the soil. When the periodic increment falls below a certain amount and becomes a slow and continuous introduction of uniform material, the single deposits blend with one another, and signs of bedding eventually escape even microscopic detection. The bedded soil thus appears unbedded, as is the case with slowly rising loess and with clay flats of the tropics and subtropics.

It is clear that bedding of a soil is connected with climate only in so far as the depth of the single striations is dependent on rainfall and on the

strength and direction of wind as well as on topographical conditions. On the other hand, a soil horizon, or a set of soil horizons, expresses the local climatic, and especially soil climatic, conditions. Horizons are distinct layers of soil produced within the bedded material by chemical change or physical translocation; each layer is the result of a diagenetic process at work within the soil. This result may be produced in three ways. It may consist simply of a chemical change unaccompanied by any transport of material, whether dissolved or in colloidal suspension. In this case no soil material is carried from one layer to another. Whether such a process is ever completely realised is questionable. The nearest instance is that of the decomposition zone of soils formed *in situ* where the rock surface is covered by such a bed. It has already been remarked that decomposition horizons of this sort provide the best example of purely chemical conversion in that the lower layers of soil often contain completely decomposed minerals whose shapes are none the less preserved intact.

In the second case, chemical change in a layer of soil may be accompanied by removal of dissolved or suspended material. The layer losing soil material is then described as an eluvial horizon, and its products of decomposition often have a far-reaching effect on the neighbouring illuvial horizon in which they come to rest. "The following symbols have lately been adopted for describing soil horizons: the letter A designates eluvial horizons, *i.e.* those from which something has been leached during the process of soil formation either by chemical or mechanical means. The letter B indicates illuvial horizons, *i.e.* those into which something has been carried; and, finally, the letter C specifies the parent material. As it often happens that one and the same horizon displays variety in respect to its morpho-

logical characters, A_1, A_2, B_1, B_2 and so forth are also used as signs" (Glinka).

Whether the illuvial horizon is below or above the eluvial horizon entirely depends on the predominant direction of water movement through the soil. I use the word predominant with intention, for reversals of water movement not only may but must occur at times whether the normal direction be upwards or downwards.

From these definitions it follows that a soil horizon as part of a soil profile may sometimes be identical with a soil bed. It need not be identical, however, and is so only in exceptional cases. As a rule, where bedding consists of deep layers a single bed comprises various horizons, and where bedding consists of very shallow layers a horizon often includes many beds.

Movement of water through the soil is predominantly downward only where the soil climate is such that the amount of water introduced exceeds the amount removed by evaporation from the soil. It is accordingly limited to subhydric soils which form in depressions under water, and to layers of which the climate is extremely humid. In its downward movement such a stream of water carries in solution not only salts and so forth derived from the mineral matter of the soil, but also soluble organic substances formed on or near the surface. These organic substances affect the whole profile to considerable depths. In addition, colloidal solutions, organic or inorganic, are carried down and with them a suspension of very fine particles. Water thus sinking through the soil may in fact be regarded as a very slow stream which finds its deepest level in the ground water, at the surface of which a well-developed illuvial horizon is usually to be found.

It is well known that the depth of the water-

table varies with rainfall. Lateral movement of ground water depends on local variations in depth of the water-table such as occur even in flat districts as a result of differences in local gradients, and depends also on the structure of the area and, in particular, on the slope of the water-bearing beds.

Except in isolated depressions the speed of the ground water stream is a function of slope and permeability of the soil. In readily permeable sands the ground water stream may reach a speed of twenty yards per hour or more where the slope is steep. In tropical decomposition zones which largely consist of colloidal substances the speed of water movement is practically nil. In such soils conditions are almost or quite stationary, at any rate below the bottom level of the water-table. A further factor is that water in the stationary zone has, as a rule, a higher salt content than the water above, and has accordingly a higher specific gravity. It thus supports the less salty water of the superior zone at levels fluctuating between the highest and lowest stages of the water-table.

If, in accordance with the convenient nomenclature described above for soil horizons, we designate the parent rock as the C_1 horizon, the decomposition zone, which is characterised by a high occurrence of pseudomorphs of the primary minerals, will be the C_2 horizon. It lies within the ground water and is completely shut off from air. The siallitic-allitic decomposition of humid tropical soils which was described above is accordingly a subhydric formation, as is further indicated by absence of any sign of oxidation within the decomposition zone. The C_2 horizon reaches the soil surface only where there is continuously standing water, and even so only if there is no deposition of material, whether by sedimentation from incoming

waters or by plant agency. If these conditions are not satisfied—and this is by far the most common case—A and B horizons automatically develop in the soil, though their thickness is irregular and may be hardly measurable. A and B horizons must develop together, for when material is carried away from one layer it must be deposited in another unless the transportation is purely lateral.

(a) *Tropical Peat Profiles*

Formations occurring below deep standing water are hardly of interest for practical pedology. If the water be removed they are converted to soils in the ordinary sense of the word, and then appear as typical subhydric gray earths, of which at any rate the surface layers rapidly undergo such changes as are imposed by local conditions. Apart from these formations, development of profile proceeds in very diverse ways, as determined by the duration of waterlogging and by the extent to which vegetation shares in the process.

Where the excess of water is so great that deep penetration of air into the soil occurs only occasionally, and where in consequence decomposition of organic residues at the soil surface is comparatively slow, tropical peat profiles are formed. These have been described above and are widely distributed in the tropics and subtropics. They are formations which depend on local topographical conditions. Their A horizon lies of course at the surface, and invariably consists of a more or less thick layer of humus, as horizon A_1, and an equally varied thickness of bleached material, as horizon A_2. This is at any rate the case with the widely distributed forest peats. Decomposition of the organic residues produces acid bodies which, just as in temperate climates, dissolve from the upper mineral

layers bases and sesquioxides, including iron, a producer of soil colour, while silica remains unattacked. The dissolved substances are carried down into the soil, and matter held in colloidal solution is flocculated in the subsoil by ionic action. This process is of course entirely dependent on the strength of the downward movement of water. For this reason deep development of the bleached zone and a B horizon showing incipient pan formation are only found in permeable and more or less sandy subsoils, whereas if the subsoil contains much clay the B horizon is only developed in spots and appears as a mottled or striated coloration of the greenish blue or gray mass of clay, while a layer of rather lighter colour constitutes the A_2 horizon. It may be noted that bleaching and so forth is more intense as the subsoil is poorer in bases, since the acidity of the products of organic decomposition is then higher. At the same time, as has already been remarked, the agricultural value of the resulting profile is less as bleaching and acidity are greater. Where the humus layer is fairly thin the depth of the bleached layer is a safe guide as to the plant-food content of the soil, since this content is smaller according as the ratio of bleached soil to humus is greater.

So little work has been done on profiles of overgrown and silted-up swamps (*Verlandungsmoore*) of the tropics and subtropics that it is not possible to give an accurate description of them. As a rule the humus layer, especially in the case of papyrus peats, is so thick that it alone is of practical interest, and is for the most part very rich in plant foods. High moors, consisting of sphagnaceae and derived from earlier forest peats, occur in the hot zones only at great heights above sea-level and need not be described in detail.

(b) *Tropical Red Loam and Red Earth Profiles of the Humid Zones*

Where movement of water through soil is either continuously or very predominantly downward, so that the soil is continuously moist, and where nevertheless subsoil water does not rise and fall in such a way as to exclude penetration of air and prevent the passage of water containing atmospheric gases, profile formation assumes quite unusual courses. Under such conditions, as has already been stated, the natural cover now consists of the tropical rain forest or primaeval forest, which year by year returns enormous quantities of organic matter to the soil. It is commonly regarded as a primary formation, and is directly associated with the production of the soil profile. This view is wrong and is the root of countless differences of opinion as to the formation of tropical soils in general, and as to the formation of red loam, red earth and laterite in particular. Never even under the most favourable circumstances can the tropical rain forest be a primary formation. Its residues can never have influenced the earliest stages of soil formation. Whenever rock material of any kind is subjected to weathering, that is, begins to change to soil, it at once affords a footing for life and, in particular, for vegetation, but primaeval forest is never its first cover. If we exclude the hosts of lower plants which prepare the way for more developed forms of vegetation, we find that the first plant association to appear is never thick forest producing much organic residue, but formations of an open character and with a very small production of organic matter such as grass, herb or bush. This has been shown by observation on newly risen islands and those which have been robbed of their plant cover by volcanic eruption.

Direct evidence is, however, hardly necessary where inference from facts is so compelling. Thousands of years must pass before primaeval forest gains a hold on the land. The influence of organic substances on soil formation also dates back thousands of years. Even where soil climate is most favourable for the development of primaeval forest there is ample time for water saturated with air to soak into the soil after each rain, and for air to penetrate behind the water up to a point at which their action ceases. This depth depends on the permeability of the soil and may be great. Within this depth soil material is oxidised, a process which principally affects iron compounds within the soil.

As a consequence of these conditions red soils, often of great depth, are first formed throughout the tropics wherever the humidity is sufficient. These soils are typical of the region, and the final development of their horizons is then a function of the increase in humus substances following an increase in plant cover. So long as the yearly addition of humus beneath an open plant formation is less than or equals the yearly decomposition—and this must be the case for hundreds of years at least—the weathering process conditioned by an alkaline or neutral reaction of the soil solution takes the mixed course described above, that is, allitic and siallitic materials are formed. Bases and silica are removed from the eluvial horizon, which is here the layer lying above the lowest level of the water-table. Iron and aluminium are at once precipitated from solution and are not removed to the same extent. The soil slowly assumes a stronger allitic character, and, if the conditions of formation remain the same with exclusion of the effect of organic substances, is finally converted to pure allite totally void of bases and silica. In a profile of this kind the red earth of the surface passes without a sharp

boundary into a mottled zone, which again changes gradually into a decomposition zone of lighter colour, and this leads without a break to the parent rock. Only in examples of considerable age does there appear, at a greater or smaller depth in the soil, a faint trace of an illuvial horizon in the shape of bog iron ore concretions which occasionally join up to form a continuous layer. These features may be observed by simple inspection. From the chemical point of view the content of bases increases very gradually from the surface downwards, while the acidity decreases with depth. Even the surface is only weakly acid, and never gives a lower *p*H than 5·5. At greater depths in the soil the reaction finally becomes alkaline. How far such a profile, which is one of the commonest of the moist tropics, has advanced towards the final product, typical allite, depends of course on the age of the particular soil formation. The younger the soil, the greater the predominance of unchanged siallitic material, and the soil has then the character of a more or less plastic red loam. As allitic material accumulates the soil takes on the granular structure of a red earth. The "heaviness" of a red soil formation of this kind accordingly provides a really useful indication as to the soil type and approximate age of the soil. The red earths and red loams differ notably not only in their content of plant foods but also in their response to manuring, and, as will be shown later, this means of discrimination is of great practical importance. When this process of profile formation takes place in rather permeable material it sometimes happens, even in the early stage while much siallitic material is still present, that layers of finely divided but strongly coagulated iron hydroxide occur at some depth in the soil. The iron hydroxide has presumably been washed down by water. In older formations the particles

are linked up by precipitation from colloidal solution of iron and aluminium hydroxides, and then often form an iron hardpan a foot or more in thickness. These pans are often a serious obstacle to the cultivation of deep-rooted plants such as rubber, even if there is no question of true cementation of the material.

Examples of fully developed profiles of this sort are always exceptional. The reason for this is clear. If neither man nor some natural occurrence intervenes to disturb the process of development, the primaeval forest eventually displaces all other plant formations supported by the extremely humid conditions of soil climate now under review. The amount of humus steadily increases, and the content of bases in the surface layers is steadily reduced by leaching. These bases serve to neutralise newly formed organic acids and sulphuric acid. The moment when the bases are no longer sufficient to neutralise the acids comes, of course, more quickly where the soil material is originally low in bases and where the age of the profile is greater. The humus layer is, as a rule, only moderately acid, at any rate at the surface, by virtue of its ash content, but below it the remaining acids now come into action both in dissolved and in colloidal form. Thereafter humus substances penetrate the immediate subsoil, which becomes more acid, and so long as the acids do not too greatly exceed the absorbed bases of the mineral sorbtion complexes the humus substances separate out at this level either as isolated gel complexes or as a coating on the mineral constituents of the soil. The layer of soil adjoining the humus layer is thus an illuvial horizon with a structure admirably adapted for cultivation and having a high content of plant foods, which are in part brought up from lower layers of soil by means of the organic residues.

The ageing of the soil by sol-weathering begins only when there is an appreciable residual acidity (exchangeable hydrogen), not more than a trace of exchange acidity (ionic aluminium) and still a considerable degree of saturation with bases. As has been emphasised above, these young soils of the primaeval forest type, formed on material rich in bases are the best cultivable soils in the world. As a rule, however, this stage is quickly passed. As soon as the reaction of the soil solution falls below *p*H 5·5 the acids have a stronger direct effect, and not only displace bases at a greater rate, but enable iron and aluminium to pass into solution and to move down both in the sol and salt forms. This effect is increased by the protective action of acid humus sols. The uppermost mineral layers of soil are then leached and lose their colour. The degree of saturation of the sorbtion complex decreases and the complex itself is attacked. Since hydrogen ion in an adsorbed state is fairly easily displaced by iron and aluminium ions, the upper mineral layers which are in process of conversion to an A_2 horizon, that is, to a bleached horizon, acquire a much higher residual and exchangeable acidity, while the *p*H value sinks and sometimes falls to below 3.

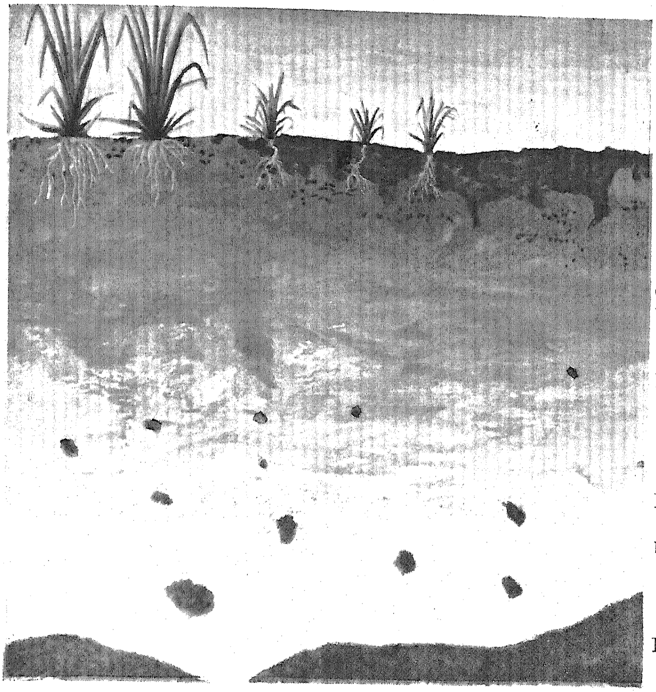
Finally, in very old formations, the small amount of sorbtion complex left in the A_2 horizon has only traces (often 2 or 3 mg. equivalents) of exchangeable bases with ionic aluminium, *i.e.* exchange acidity of Kappen, equal to the amount of hydrolytic acidity. These are the signs of the extremely old soil which, however, is of the siallitic type, since the acid reaction prevents the removal of silica and accelerates that of sesquioxides. The processes discussed above are reversed when the soil becomes acid. This interrupts the accumulation of allitic material, which requires a neutral or alkaline reaction in order to reach its final stage.

Siallitic residues gradually accumulate and may even be resynthesised as allophanoids.

Below the newly formed eluvial horizon there appears a new illuvial horizon at a point where acid action ceases. In it bases and sesquioxides accumulate, as may be detected by chemical examination, but is sometimes made evident by the beginning of iron pan formation. At greater depths in the soil the effect of the acids is no longer felt, and accordingly the red soil, the mottled zone and the zone of decomposition have a weak acid and, finally, an alkaline reaction. The structure of the profile as described above and its allitic-siallitic character remain unchanged, and indeed, if the influence of organic matter has started at a late stage in the evolution of the profile, the lower part remains chiefly allitic. Plate VIII illustrates a mature profile of a primaeval forest soil of this kind. In these soils a further illuvial horizon is often formed at the ground water level in the form of a clay layer, or of a hard layer cemented with lime or silicic acid. In the Dutch East Indies these are called *Padas* or *Tjadas*, although the same word is used for stony or other layers of erupted material occurring in volcanic soils. When such layers occur near the surface they form, of course, a serious obstacle to cultivation and must be avoided with care.

It was noted above that where the process of soil formation has not been interrupted in the geological sense primaeval forest vegetation usually obtains a hold while the profile is still in an early stage of development, that is to say, before it has changed into an allite. For this reason primaeval forest soils are almost without exception red loams, and are for the most part heavy soils with a high base-holding capacity. The character of an individual soil formation depends in the last resort

PLATE VIII: Red Earth Laterite



on the history of the vegetation in that particular place, and it follows therefore that all possible intermediate forms must occur, and these are in fact to be found. Heated controversies as to whether allite can be formed or occurs below primaeval forest are numerous enough to fill a library, although a careful study as to conditions of formation, in conjunction with the examination *in situ* of numerous profiles, immediately supplies the answer that allites are certainly not formed under primaeval forest but very often persist there.

Whether such formations are rightly called fossil laterites, or whether the whole profile may be described as degraded, as is sometimes done, is another question. Fossil soils in a strict sense are only those whose development is completely arrested and which, removed from the action of weathering, undergo no further change. This obviously cannot apply to any soil profile that is continuously changing. On the other hand, even moderately deep profiles may show that the commencement of profile formation must lie in earlier geological times, so that different climates have affected the process. As against this it must be admitted that in the tropics the influence even of the ice ages is, on the whole, very small. The expression "degraded" allite and so forth is a purely verbal conception which has no place in soil science, and, moreover, in so far as it implies impoverishment, it is false as often as true. Thus in the hot moist zones pure allites which are not "degraded", *i.e.* which have not been modified by the influence of humus, are much more impoverished in respect to those constituents that affect human cultivation than quite an old "degraded" primaeval forest soil, and compare still less favourably with younger soils of that type.

The changes in soil material and the formation

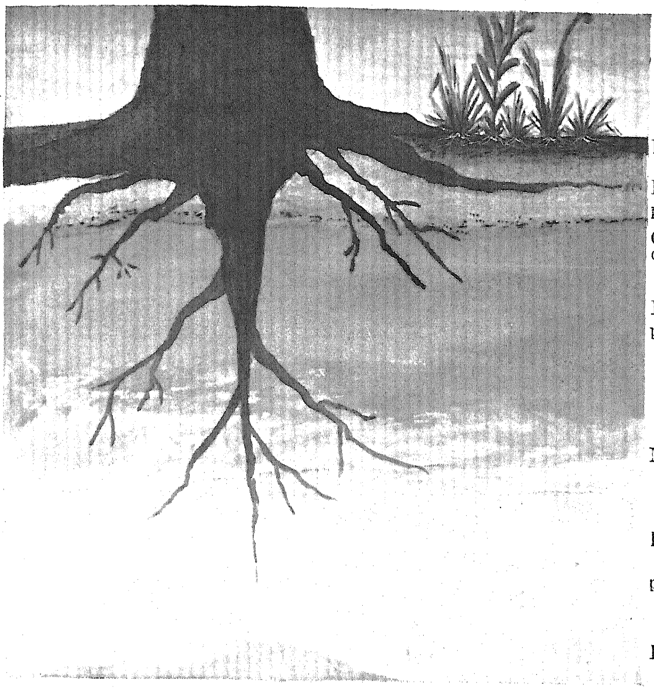
of the primaeval forest profile which we have been considering are, however, an exact tropical and subtropical parallel to podsolisation.

In the subtropics the brilliant red soil colour is, as a rule, displaced by a browner shade. Brown earths and brown loams take the place of red earths and red loams, although it is not at present possible to explain this very striking change, which is particularly evident as one ascends any mountain in the tropics.

The yellow earths and yellow loams which are widely distributed through the moist tropics and subtropics are to be regarded as a separate soil type only in so far as their colour affords a convenient distinction. In their development they are either early antecedents of red-coloured soils or, even more frequently, they are red soils bleached by humus. Finally they occur wherever the iron content of the original soil material is too low for development of the deeper colour. Where the content of iron is exceptionally low, gray earths may be formed in absence of subhydric conditions, but such soils are very rare and of restricted local occurrence.

Although in general soil colour is largely dependent on the iron content of the soil material (and in some cases on its content of manganese and titanium), being darker where the content of iron is higher, yet there is one notable exception. All limestones, almost without exception, even though they contain but a trace of iron, yield in a hot moist climate exceptionally bright red soils which sometimes take on an allitic and sometimes a siallitic character, and apparently correspond to the *terra rossa* of the semi-humid, semi-arid zone which also occurs exclusively on limestone. Apart from superficial podsolisation which, as would be expected, takes place in these *terra rossa* soils when under primaeval forest, there is a very noticeable

PLATE IX: Red Loam



Humus 10-15 % pH 4-6

Bleached horizon
pH 4-5

Commencement of
concretion formation

Red loam
pH 5-6

Mottled zone

Decomposition
zone
pH 6-8

Rock

absence of horizons, and in particular one never finds even a suggestion of a decomposition zone. The red soil invariably lies directly on the limestone, which is often a gleaming white. The problem as to how these soils have been formed is as far from solution in these regions as it is elsewhere. It is indeed hardly possible to decide what is imported material and what is residue left by dissolution of the limestone. In most cases both factors have probably contributed to the formation.

The soils we have been considering are formed *in situ*. When attacked by heavy rain they can of course produce enormous secondary soil formation. The character of such transported soils will evidently be very largely determined by that of the original material. It must be noted, however, that the secondary soil formations are subject to the same influence of local weathering and leaching as are soils formed *in situ*, and their upper layers will be predominantly siallitic or allitic according to the vegetation they support.

(5) Soils of the Intermittently Moist Tropics and Subtropics

Soils of the tropics and subtropics formed where the soil climate is continuously moist and warm show, on the whole, a noticeably uniform development along the lines described above. This is no longer the case in an intermittently moist climate in which occurrence of ample soil water alternates with periods of dryness and where, as a result, the direction of water movement in the soil is reversed, sometimes repeatedly, during the course of the year. Such frequent reversals are quite common in the transitional area bordering the humid region. In such intermittently moist districts the observer is met by an extraordinary diversity of what seem

to be quite heterogeneous soil formations. This is so since, as would be expected, all topographic and geological petrographical factors are much more prominent than in areas which are always moist. The change becomes more pronounced in arid areas where, in the phrase of E. Kaiser, "edaphic factors" become dominant.

In the moist regions the most useful basis of classification was evidently the distinction between places in which excess water continuously excluded air from acting on the soil and those in which air had access to the soil. Where air was excluded for long periods one expected to find developing a constantly moist bed of humus of varying thickness. In regions which are only intermittently moist the plant formations—monsoon forest, savannah and tall grass steppe—are much less dense and, as has already been mentioned, the yearly addition of organic matter to the soil, though not inconsiderable, leads to what is, in comparison, a very small formation of humus, since the organic matter is exposed to light and air by the loose plant cover and rapidly decays. There is therefore no question in these regions of a long-continued exclusion of air by a bed of humus. Such a bed can be formed only occasionally when there is excess water and, if pronounced dry periods occur, is of course dependent on the amount of excess water and the time it stands. The more impermeable a soil material the less water penetrates to the subsoil and the longer water remains on the surface. So also the amount of water is greater if it is derived not only from purely local rainfall but by periodical accumulation from adjacent areas either by sheet flow or by inundations.

It has already been noted that, owing to the rapid run-off of rain water, which falls chiefly in heavy downpours and has not time to penetrate,

even the most gentle slope is withdrawn into more arid conditions of soil climate. There is accordingly a much sharper distinction between soils of the heights and slopes and soils of the depressions—taking depression in its widest sense—than there is in districts which are always moist. In the intermittently moist region the red soils of the upland pass without transitional forms into the more or less reduced dark or black soils of the hollows.

(a) *The Red Earths of Intermittently Moist Climate*

During the rainy period there is no difference between weathering conditions of the intermittently moist monsoon forest and savannah climate and those of continuously moist and hot climate. Decomposition zones of a mixed kind are formed, and wherever air can gain sufficiently free access, as is, for example, the case where solid rock lies below an accumulation of detritus, the surface layers undergo oxidation and are red although the climate is only intermittently moist. The reaction remains either faintly acid or alkaline, so that sesquioxides are protected to a large extent from being washed away. Even in the older formations no modification is imposed by the appearance of large quantities of organic acids, so that allitic material gradually accumulates in the soil mass, whereas bases and silica are sometimes strongly leached and carried down into the ground water, since even here precipitation is still heavy.

This transportation is, however, subject to big interruptions owing to the dry seasons when, in consequence of strong evaporation from the soil surface, water movement within the soil is reversed for long periods, that is, water rises upward from below. In this there is no true capillary movement, *i.e.* movement through distinct columns of water, but

chiefly a transfer of water from one particle of soil to the next, together with a certain upward movement of water in the form of vapour. The result is that during every dry season some bases and other substances are again brought to the upper layers of soil from the lower layers, and the weathering process and, in particular, leaching go very much more slowly than in continuously moist climates.

In this way predominantly allitic red earths are formed *in situ* with quite deep profiles tending to show a granular structure. There is no surface layer of humus, although the upper layers may be permeated to some degree by organic substances. Below this the red earth changes gradually into the decomposition zone of the deep subsoil. These red earths thus agree in all respects with the early stages of the red soils of the constantly moist tropical climate, with the difference that they preserve their youth longer than the latter owing to less vigorous leaching and a correspondingly higher content of bases.

Red earths of the highest agricultural value are thus to be found in huge areas under monsoon forest, savannah and tall grass steppe. They are in no way inferior to the best primaeval forest soils as cultivable land, and, indeed, in the case of young formations, they are on the average superior. On the other hand, even in the younger formations the content of nitrogen and of humus is lower. Only below the monsoon forest do the upper layers contain as much as a few per cent reckoned on the dry substance. Rock fragments included in the soil column, or, should these be absent, mineralogical analysis showing the amount of silicate not yet decomposed, afford a sure guide to the age of the soil, and are therefore of great use in evaluating the soil for practical purposes.

In such a red earth, as soon as the last trace of

rock is decomposed and as soon as the leaching of bases, accompanied by appearance of acidity, amounts to 50 per cent of the sorbtion capacity, the development of the soil profile takes a new and characteristic direction as a result of the occasional upward movement of soil water.

At this point the sesquioxides become mobile in the water, which is low in cations. They are peptised, to use the current phrase, and enter into solution as colloids. It is probable that traces of silicic acid play an important part in this. In addition a solution containing sesquioxides rises from the subsoil. In the dry season these sols, together with bases and what is left of the silicic acid, rise to the surface where, under the influence of heat and drying, they are irreversibly coagulated, that is, they are no longer able to pass into solution. This process is strongly assisted by capillary action. The following rains dissolve out what salts and bases are present, but can wash back into the subsoil only minute traces of the sesquioxides which reached the surface and were there consolidated by coagulation. In this way the superficial layers of soil are enriched in sesquioxides by numerous repetitions of this process. The illuvial horizon is thus caused to lie above the eluvial horizon. With continued addition of allitic material the siallitic material which is still present and still subject to decomposition steadily decreases in amount. The surface layers change to allite laterite, which finally contains up to 90-100 per cent of hydrated sesquioxides. Owing to the tendency of iron hydroxide to pass into limonite, the surface of such soils is finally covered by an iron crust, often of wide extent and reaching to considerable depths. The crust consists of cindery limonite concretions; at greater depths, which escape the extremes of heat occurring at the surface, it has a cellular structure with interstices occupied by

aluminium hydroxide partly converted into hydrargillite, together with residual and newly formed siallitic material. Below this illuvial zone or zone of enrichment the soil layers are correspondingly impoverished in sesquioxides. In deep earths where the impoverishment extends through the whole thickness of the deeper profile the effect is evident on simple inspection. Where the profile has developed on solid rock and is accordingly shallow, and where the crust or zone of enrichment lies directly above the decomposition zone, signs of impoverishment are very indistinct. As a rule iron compounds accumulate in the upper layers of soil and aluminium compounds in the lower layers.

It is clear that extensive removal of bases which precedes the formation of laterite impoverishes the soil and prohibits any really vigorous vegetative growth which would otherwise change the course of the soil-forming process by its residues. The iron crust, even in the first stage of its formation, is of course completely inimical to plant life. Only in cracks is there some scanty growth, as is shown diagrammatically in Plate VIII. The widely held opinion that primaeval forest soils are often degraded laterites is therefore a complete inversion of the facts and arises through confusion of early allitic formations, which, as was explained above, not only may but must occur below primaeval forest, with true allite laterite which is in process of formation by secondary accumulation at the soil surface. The latter is undoubtedly the final product of all soil formation and is less soil than rock, and, moreover, a rock which cannot be changed back again into soil by any conceivable process once a certain stage of maturity has been reached.

That all lateritic red earths and, a fortiori, all definite laterites have little or no agricultural value is evident. Complete absence of undecomposed

minerals in mature red soils, and the appearance of pea iron ore and other limonitic concretions at the surface, are not to be overlooked as danger signals in assessing such soils for cultivation. Soils of this kind are, as a rule, exceptionally poor in all bases, although their reaction may be neutral or only faintly acid. In addition to this, owing to removal of siallitic material they usually lack absorbing complexes and have therefore lost the power to retain bases. They are rich in phosphoric acid, which according to recent work seems to play a part in peptising the sesquioxides and, probably for this very reason, accumulates in the concretions. Pea ore from laterite sometimes has an extremely high content of phosphoric acid, up to 3 per cent and more, but as was stated earlier the value of this total phosphoric acid is not great.

Attention was drawn on page 70 to the easy confusion of laterite iron crust with bog iron ore, which is also known as savannah iron ore. These concretions when examined under the microscope display quite a different structure, and are not, of course, any guide as to the worth of the soil. They occur on and within slopes which encircle accumulations of water, and there often form considerable beds which, in British East Africa, are called *marrum*. As they often extend far into the soil they can be very troublesome obstacles to cultivation. As a rule their manner of occurrence clearly shows how they came to be produced and makes it impossible to associate them with laterite.

A third kind of concretionary formation occurring in the red earths of intermittently moist climates consists of lumps or beds of limestone or lime silicate. Those usually lie at a shallow depth, and are of local occurrence where either the parent rock or adjacent materials subjected to leaching make it possible for lime to accumulate. These formations

are comparatively rare, and as the beds never extend far they are in practice of quite local interest.

For the brown earths of the intermittently moist tropics reference may be made to what was said in the case of continuously moist climate.

Yellow earths hardly ever occur here as bleached red earths, but are widely distributed as early stages of red earth formation, especially on material comparatively poor in iron.

As has already been noted, the influence of the parent rock and, as far as soil colour is concerned, the rock's content of readily oxidisable iron compounds play a much more prominent part where the climate is only intermittently moist. The most pronounced red earths are associated with basic rocks rich in iron, as, for example, biotite and gneiss containing hornblende. Only limestones maintain their strong tendency to form *terra rossa*, and this is actually accentuated under the conditions described.

(b) *Gray and Black Earths of Intermittently Moist Climate*

In intermittently moist regions where the parent rock is of low iron content gray earths formed *in situ*, *i.e.* resting on the solid parent rock, occur to a rather limited extent, but are nevertheless much more often seen than in the moist tropics. This agrees with what has already been said and requires no further comment. Gray earths and black earths are, however, fairly widely distributed below tall grass or herb vegetation, even where the chief colouring material of the soil does not consist of reduced, more or less insoluble compounds of iron, together with some humus, as is the case in depressions.

A necessary condition for the conservation of humus as a colouring constituent is retardation of

oxidation, that is, there must be periods of excess moisture, a condition which can be satisfied only by large periodical influx of water. The extent to which humus is conserved, the form it takes, its distribution in the soil and accordingly its visible effect on the soil profile, are, however, further dependent on the degree and kind of base saturation still present in the soil material.

In the intermittently moist region the reaction is more or less alkaline or neutral and the content of bases is high. Decomposition of organic residues is rapid, and so the amount of residual humus is much reduced. At the same time there are dry periods which lead to dehydration of what organic material is left, and this is to some extent charred and converted into humus charcoal, or is at any rate changed to dark humus substances of very high carbon content which have a strong colouring action. If alkalies predominate in the soil these humin salts are more or less soluble; if calcium predominates they are insoluble.

Where the soil is permeable, characteristic profiles are thus formed under scrub forest and savannah and, less frequently, under tall grass steppe. In these a surface horizon of very dark colour, but containing a comparatively small amount of humus, passes gradually into a subsoil which is usually red or brown. The gray or black earth of the surface soil of varying depth thus lies above red or brown earth, and although there may be no sharp boundary the two horizons may be clearly distinguished.

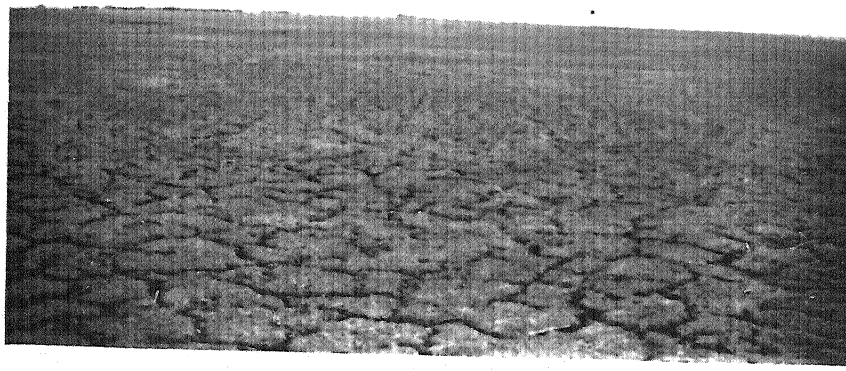
Where the subsoil has a specially high content of alkali bases, as, for example, in volcanic ashes, a dry turf layer is sometimes formed a few inches, or at most a foot or so, in thickness. Below this there is usually a slightly decolorised or lighter eluvial horizon A_2, and below this again there is usually the red earth layer of the subsoil.

Profile formation has a quite peculiar character in all clay flats and depressions. Since very contradictory views have arisen as to the evolution of these tropical and subtropical black earths, which include the famous *regur* of India and the *tir* of Morocco, and have many parallels in other continents, we shall here describe their formation in detail by using the careful investigations of Joseph, Greene, Grabham, Colchester and others in the Sudan, where the conditions of formation have been studied on the spot.

These clays are for the most part very heavy, and in consequence of their low permeability infiltration with humus substances can occur only to very small depths. In spite of this, the content of organic matter in these soils, which sometimes exceeds 8 per cent, hardly changes through a depth of several yards, and yet there is hardly a sign of bedding such as must appear if these were definite swamp formations, as has been suggested by way of explanation. A further reason against ascribing their origin to sedimentation alone lies in the admixture of coarse-grained material with the clay, this feature being sometimes well marked, and in the occurrence of hard concretions of calcium carbonate in the lower soil horizons. The two features in conjunction make it at least very improbable that these peculiar soils are aeolian formations, as is often thought, quite apart from the fact that the heavy clay character of these soils makes this unlikely.

If these soils are examined on the spot without preliminary bias they give the impression, which seems paradoxical at first sight, that the whole soil material is very carefully and deeply mixed, since otherwise the features just noted are quite inexplicable. This is in fact the case. These soils are thoroughly mixed to the depth, often several yards, to which cracks extend. The cracks are

PLATE X



DRY SEASON CRACKS OF A CLAY FLAT, TALL GRASS VEGETATION BURNT OFF

formed during the dry season, owing to the heavy character of the clay flats and depressions. Plate X, "Dry season cracks in a clay depression", gives a good but by no means extreme display of the cracks which form year by year, and solve the puzzle we have been considering. The breadth of the crack is often 4 to 8 inches or more, and they penetrate several yards into the soil. I myself have measured depths exceeding four yards, and this cannot be the maximum.

It has been repeatedly observed that by means of these cracks considerable quantities of soil material must be carried by wind and water from the surface to great depths within the soil. This in itself constitutes an energetic mixing of soil. A more important and more powerful factor, however, is the displacement of deep-lying soil material which is necessarily set up by this introduction of solid matter when the soil is again moistened and when the cracks close up by swelling of the colloidal masses. This leads to a pronounced circulation of soil material upwards from below, and thereby to complete mixing of all soil layers up to the depth reached by the cracks. This process is responsible for the characteristic profile of tropical and subtropical black earths, since they all have the same general character.

The forces involved are strikingly evident in well-marked slip surfaces within the lower soil horizons, as may be readily seen during excavation of canals and so forth. This soil circulation is a long-period process, but is not so slow as might be thought. On the big clay flats of the Sudan, for example, walls and buildings get out of plumb and even fall within a few years, so that the speed of the process should not be underestimated.

The character of these black earths in individual cases is, of course, entirely dependent on the com-

position of the clay material. The soils are all heavy, which is indeed the origin of their special mode of development. Where alkalies constitute the major part of the absorbing complexes they are, without exception, of very low permeability and are exceptionally heavy to work, while in the dry condition they form hard lumps. With increase of calcium in the complexes the soils tend in the dry state to assume a crumbly or dusty condition, and are accordingly easier to cultivate.

In the latter case, as has already been noted, calcium carbonate concretions in the form of cornstones (*Lösskindchen*) are present in these soils. They are doubtless formed in the surface layers, but owing to soil circulation are distributed throughout the whole profile and occur also at the surface as *Steppenkalk*. As a rule these concretions acquire coats of iron and manganese by long exposure at the surface, and are easily confused with iron concretions. Salt horizons are not usually formed in these soils in the intermittently moist regions, since leaching and salt accumulation are more or less balanced in the surface layers of soil. The cultivable value of these soil formations is to be assessed with great caution, and here, if anywhere, generalisations and conclusions based merely on superficial similarities are dangerous and misleading.

The inexhaustible fertility of the Indian *regur*, also called "black cotton soil", is world famous. For hundreds, probably for thousands, of years it has produced good crops without any considerable manuring. Black earths apparently very similar may be the reverse of fertile, especially if alkalies predominate. This is chiefly due to the unfavourable physical properties and reaction which depend on the alkali content, although intrinsically the soil may be rich. Under specially favourable conditions of weathering such soils may, however, be of value.

At any rate the large majority of these soils responds wonderfully to drainage and cultivation, provided that the base content is not so high as to give a reaction much above pH 8·5.

During the pronounced dry season crops are endangered by cracking of the soil, which leads to tearing of the roots. Nitrogen is almost always extremely low in accordance with the low humus content of this soil type with the exception of the *regur*.

Throughout the world the original vegetation consists of tall grass with occasional trees.

(6) Soils of Tropical and Subtropical Dry Climate

In atmospheric climate an area may be called dry if yearly evaporation from a free water surface exceeds the amount of water falling as rain. On the basis of this definition a large part of the areas designated intermittently moist falls within a region of dry climate. In respect to soil climate an area is dry if the precipitation is so small that it does not penetrate sufficiently deeply to reach the ground water if such be present. This may happen on very permeable soils such as the lighter sands, or in more or less isolated depressions. The latter may, however, also locally enjoy a rather moister soil climate and even have excess water at times. The region so defined has a climatic limit in a precipitation of about 600 mm. It includes therefore in the tropics and subtropics the far-spread climate of the steppes and deserts. Within the former the regions of dry forest and scrub also fall.

Since the amount of rain is small, and since it usually has but little time in which to act upon soil material, chemical weathering is much retarded,

and in particular there is little production of clay. To this may be ascribed the preponderance of light or sandy soils in the dry regions, except where clays have been formed by inundation from rivers or by deposition from sheet flow. The formation of red earths, which require thorough decomposition of rock material, is accordingly restricted to localities in which the soil climate is more favourable by reason of occasional influx of water. Such are the west slopes on the weather side of mountains or mountain ranges. Even here, however, red soils occur for the most part only where the parent rock is rich in iron: brown, yellow and gray soils predominate. The older limestones are an exception even in the dry regions, for they often form deep *terra rossa* soils which extend far beyond the subtropics into the northern coasts of the Mediterranean.

At the edge of the dry area decomposition zones are not quite absent from soils lying on solid rock, but they are very much less thick than in regions having a moister climate. They also occur in deposits of rock debris, and are then usually fairly firmly cemented and have accordingly been described in geological literature as conglomerate or breccia.

In the red earths formation of horizons is limited for the most part to the appearance of calcium carbonate concretions, which may be discrete or united to form a bed. They are absent, strangely enough, just where one would most expect to find them, in the *terra rossa*.

Defective leaching produces specially characteristic features in the brown, yellow and gray earths which, for lack of intense decomposition, predominate in the dry region. Leaching is defective because rain does not soak into the soil sufficiently far to join up with the ground water, and for most of the year there is an upward movement of water through

the soil. The effects are more clearly shown because most arid soils have a low sorbtion capacity: only a small amount of bases can be held in combination and a comparatively large amount of free salt remains in solution.

In this connection we must exclude very light sands which, even in the dry regions, are often leached to great depths. Such soils, for example, extend for thousands of square miles in the Myombo forests of Central Africa. In these rain water penetrates so quickly that, once deep in the soil, it does not move upwards again, and there is accordingly no possibility of salt solutions rising from below. With this exception the entire dry region is characterised by the appearance, at a greater or smaller depth, of illuvial horizons of which the eluvial horizons lie still deeper in the soil. The latter are in fact to be found at the bottom of the layer of soil which is moistened during the rain season, and which may be widely separated from the ground water, if there be any ground water, by a layer of dry material. As a rule heavier rainfall is associated with deeper occurrence of these horizons, which are for the most part derived from adjacent material and tend to form beds. In desert climates they often reach the surface and then form crusts which are indeed to be found in all climates on rock and on rock debris, since in all climates the arid conditions which are necessary for their formation may be realised on suitably exposed places. Thus, as has recently been shown by various writers, the so-called desert crusts which consist of iron and manganese compounds are by no means limited to desert climates, although it is only here that they have a regional distribution, whereas in moister climates they occur only locally.

In areas lying on the boundary between semi-arid and a moister climate the brown or gray soils

of the steppes and dry bush show no obvious profile formation, for although formation of an illuvial horizon can be detected chemically it escapes the eye. The remarkably deep loess formations are a special class and, as has already been noted, they show no tendency to form horizons. Only at the edges of depressions, into which considerable quantities of suspended matter are brought from time to time by sheet flow and then to some degree penetrate into the subsoil, is there usually found a characteristic illuvial horizon. This results from the introduction from above of clay or fine soil material, and from the upward movement of saline ground water. For want of a better name I describe this as a cementation horizon. During the rains these soils, which form a wide circle around almost all depressions and are often of great extent, show the behaviour which one would expect from a sandy clay. In the dry season, however, the cementation horizon becomes almost as hard as stone. The cementation horizon may extend almost to the surface. It is almost impossible to penetrate more than an inch or two into these soils by means of tools, even with augers, and yet when exposed to the air they quickly break down, even without moistening, into a friable mixture of sand and clay. Where lime-bearing material occurs, huge beds of limestone are formed at the edges of depressions. These have already been mentioned under the head of secondary rock formations, and when again exposed to weathering they form, as has also been noted, the gray dust soils of the lime pan areas.

In the boundary area the heavy gray earths occur only in depressions which are more or less clearly defined. Their content of humus is, as a rule, too small for development of black shades. In arid conditions the surface layers are at times

brown, and at a small depth below the surface weak horizons of gypsum and calcium carbonate are usually to be found, but these substances do not, as a rule, join up to form solid beds. On material rich in calcium much *Steppenkalk* (nodules of calcium carbonate) is always produced. Accumulation of alkali salts in the surface layers is, as a rule, to be detected in the boundary region only by chemical analysis. In this area also the reaction of the soil always lies above the neutral point but seldom exceeds pH 8·5. Only where large amounts of salty water accumulate in depressions and, owing to impermeability of the soil, there evaporate are salty clays to be found. These form polygonal cracks during the dry season, and the salt content of the soil is largely due to introduction from adjacent areas. It is evident that the amount of salt so introduced must be large in an area where leaching is slight and where the surface layers of all soils receive a secondary enrichment in alkali salts. It is clear also that all these clay hollows and clay flats show to a high degree the phenomenon of vertical soil circulation as described above, since in this region the cracks formed on drying are specially well developed.

The colouring material of the semi-arid gray earths must be, in the main at least, iron compounds, together with some manganese. As would be expected, there is throughout the soils of this area no impoverishment in respect to bases; on the contrary, all show a certain excess of free salts over their various sorbtion capacities, these being low in sandy soils but very high in heavy soils. All the soils are thus potentially salty soils, and are at best neutral and more usually alkaline. The actual pH value depends on the composition of the salts in the soil, and this in turn depends on the composition of the original material. Where chlorides and sulphates predominate the reaction is either neutral

or only slightly alkaline even in definite salt soils. As soon as carbonates predominate the presence of calcium carbonate in excess brings the reaction up to about pH 8·5. Higher figures are a sure sign of alkali carbonates, and notably of sodium carbonate.

From the agricultural point of view these soils, which commonly carry thorn bush vegetation or low grass, are decidedly rich and give excellent yields under irrigation. To this is due the renown once enjoyed by the old agricultural centres of the world, and even to-day these soils are chosen for irrigation projects. In such schemes careful supervision of watering is always necessary. For, apart from the fact that irrigation water always introduces by no means negligible amounts of salt into the soil, the increase in the water of the soil leads to a greater concentration of salts in the upper layers as a result of evaporation. This is particularly the case when injudicious irrigation has so raised the level of ground water, which under natural conditions is very deep, that it again comes within the reach of surface processes, even though still at some distance from the surface. As a rule accumulation of salt then proceeds so quickly that within a few years, as has been demonstrated by countless examples of such irrigation projects, the whole area becomes useless for any kind of cultivation. This danger is specially acute in soils of definitely arid climates, the domain of the desert steppes and deserts, in which the yearly rainfall is either extremely small or is limited to irregular episodes. This is the true home of salt lands and salt crusts, except where the soil material is so coarse in particle size as to obliterate the picture.

Thick crusts of calcium carbonate coat not only entire soil complexes but also many rocks. Crusts and beds of gypsum develop in many desert steppes which have often a loess-like soil. After a fall of rain

temporary efflorescences of salt are to be seen pretty well throughout.

All the heavy soils in inundated areas and depressions are very saline, and in salt content and reaction form an extreme case of the corresponding formations of the semi-arid climate. There is a difference, however. In the semi-arid climate the salt horizons are more or less latent. In arid conditions the salt horizons become visible to the eye in spite of the automatic circulation which occurs in these clay soils. The appearance and chemical composition of the horizons vary with the locality. The soils show for the most part a number of horizons which are sharply distinguished, not only by their colour but also by the amount and kind of salt present in them, since the salts arrange themselves in the soil profile in accordance with local conditions of solubility. It may be noted also that the zonal distribution of salts varies, often rather widely, in regular relation to the yearly excess of water.

In areas of this kind experiments have shown that no crop plants can stand salt contents considerably exceeding 0·3 per cent soluble salts, although there are many uncultivated plants that thrive under such conditions. The salt content of a soil and the disposition of its horizons is accordingly the chief determining factor in assessing the value of the soil, which is generally abundantly provided with plant foods. Costly cultural operations are needed to make any great change in the salt content of a soil, and the process is completely successful only where the soil is not so heavy as to inhibit thorough leaching.

These conditions in many ways resemble those of salty soils of temperate regions, but differ in that humus substances are of minor importance, whereas the formation and displacement of salt horizons is

more intense; they must of course receive most careful consideration in the development of irrigation schemes. In this connection the well-designed irrigation schemes in the Sudan form an instructive example.

Wherever cultivation is made possible by an ample early flow and by a sufficiently large total volume of water the soils of the arid climate are to-day among the most fruitful in the world, just as was the case in Babylon and in Egypt, where they supported the highest levels of mankind's early culture.

CHAPTER VI

SOIL SELECTION

If the causes of failure of agricultural undertakings in the tropics be submitted to a critical examination, a surprising, but none the less understandable, result is reached. Well over 75 per cent of all failures of agricultural enterprises are due mainly, if not entirely, to wrong choice of land. In some cases it has been found that the soils were not worth cultivation, as their properties were generally unfavourable; in some cases the soils were in no way suited to the crop that was planted, in others the soil was comparatively poor and required heavy outlay on manures before giving an economic return. Irrigation schemes have sometimes been ruined by want of foresight in respect to the necessity for drainage, and projects which prospered at first are at death's door after a few years of success.

This result is surprising, since in temperate climates study of the soil and agricultural technique are long-established, and failures that occur are chiefly due to bad management. The result is intelligible, on the other hand, if one considers that the tropics and subtropics still consist for the most part of new country, and the experience is lacking which would make possible a judicious selection of soil. This, however, only increases one's astonishment at the haphazard way—there is really no other word for it—in which soils are often chosen by those who

either carry out or guarantee enterprises involving very great outlay of capital. The pernicious maxims that everything grows well in the tropics, and that crops will of course thrive more vigorously where the natural cover of the soil is denser, and that primaeval forest vegetation is invariably a sure sign of fertile soil, seem to be ineradicable, although the majority of those who argue thus do not even know what primaeval forest looks like, but apply the name to any moderately dense growth of trees.

In point of fact, in the tropics and subtropics, just as in temperate regions, it is impossible to grow any and every crop on any and every soil whether irrigation be applied or whether rainfall is sufficient. One may even say that most tropical crop plants have far stricter requirements for various definite soil properties than is the case with the majority of crop plants in the temperate zone. The argument "where natural vegetation is luxuriant crops must do well" has a kernel of truth, but it is by no means a hard-and-fast rule. It is largely because this limitation has not been recognised that much capital has been lost in the abandonment of plantations. From the practical point of view it is accordingly important to discuss in some detail the considerations which should be borne in mind when choosing land for an undertaking in the tropics and subtropics. It will not be possible to review all conceivable conditions, since these vary from case to case, but we should be able to clear up the more obvious misconceptions.

The man who undertakes any sort of agricultural enterprise in the tropics or subtropics is at once faced with a problem which for his fellow in temperate climates is much less sharply defined. Even where conditions are most favourable high freights must be paid on all imported and exported goods. These charges fall on all manufactured goods

that he imports and on all his deliveries of raw material to factories at home. The tropical agriculturalist cannot possibly avoid the latter charges, although he can reduce them to some degree by increased mass production and by cutting down, as far as may be, the cost per unit of collecting his produce. The amount of freight that has to be paid on imports depends largely on circumstances. The extent to which freight charges under this head can be reduced is determined by the extent to which importation of the means of production is required by the undertaking in question. Artificial manures are among the most important of such means of production in the case of agricultural enterprises if it is desired to maintain maximum production, and even on the richest soils artificial manures become a necessity in the course of continued cultivation. The stage at which application of fertilisers becomes necessary for production of satisfactory yields invariably depends on the richness of the soil chosen, and this determines also how long the soil can be worked on its reserves without injury, provided of course that the physical condition of the soil is good. If a locality which is under consideration for development is badly placed in respect to world markets, selection of soil must, other things being equal, be correspondingly strict. Soils which would be of high value where selling conditions and trade are specially favourable, since they then repay by high yields the cost of intensive cultivation, and in particular the cost of fertilisers, cannot as a rule be used for this purpose, nor even for large-scale farming, if they are a few hundred miles away from such facilities.

To emphasise these very obvious considerations may perhaps amuse the reader who has a commercial bent. However, although they may seem out of place in a book about soil science, they are

needed under the practical conditions of colonial areas. Not only big undertakings under commercial management enter these fields, but also ever increasing numbers of single pioneers in pursuit of an illusory independence. Intoxicated by the idea of becoming masters of many acres at a bargain price, these men settle in districts where even the most inexhaustible soil could not compensate for inadequate conditions of communications and trade, and where development of mediocre soil leads with absolute certainty to speedy disaster, which comes perhaps when the high yield obtained in the first harvest taken from the virgin land has brought about a further extension of the enterprise.

The guiding principle in choosing land should always be the well-established rule, that poor soil with good transport and trading facilities is better than good soil without.

For the choice itself two cases are conceivable: (1) one chooses the best soil from those available in a district and then selects a crop according to the special properties of this soil, or (2) having some particular crop in view, one chooses what is relatively the most favourable soil of the district.

The latter is normally the case with big undertakings, and there is then usually more scope in the choice of localities as such. The former case is more usual for the single agricultural pioneer who may have little experience of the tropics and is naturally inclined to try a variety of crops. As to choice of locality, he is generally much limited by laws regulating settlements. In both cases exact knowledge is needed as to the soil requirements of tropical crops from climatic, physical and chemical points of view.

Climatic requirements will not be discussed here. Of other requirements by far the most important

are the physical, since the physical properties of soil, which determine its behaviour to water and to air, can be modified by cultivation only to a limited extent in the accessible surface layer, but have to be taken as they are found in the case of the subsoil. Now, with few exceptions, all tropical crops and specially tree and bush crops are comparatively deep-rooting. It follows at once that the depth of soil and the soil profile in its physical aspect play an important and often decisive part in respect to all tropical and subtropical crops, whereas this is much less important in temperate climates.

The first task in soil selection is accordingly a conscientious examination of the soil profiles typical of the district. In this it is not only the thickness of the humus layer, if any, that is of interest but also the depth of the underlying uniform layer of soil substance down to the first well-marked layer or change of soil horizon. Such a change may be of two kinds: the lower layer may be much more permeable, as is, for example, the case if layers of sand occur, or the lower layer may be considerably less permeable than the upper layer and may indeed be quite impermeable, as often happens with illuvial horizons. In the latter case hard pans may be formed, that is, beds of material so closely cemented as to be impenetrable not only to water but also to plant roots. Another possibility is the accumulation of salts in such large amount that, although penetration of water is not inhibited, no root can live in such a layer.

It is of course essential that in the profile under examination ground water does not stand so high as to limit root development by excluding sufficient air. As a general rule one may take it that at any rate the zone of lateral roots of crop plants must be permanently above the water-table. This means in the case of almost all crops a minimum depth

of 18 inches free from ground water. Plants, such as rice, which grow in swamps are of course not affected by these considerations, and in the other direction tea and coffee are also excluded from the generalisation, since they are highly susceptible to stagnant ground water and cannot tolerate even occasional flooding.

What is the effect of a sand layer where ground water is normally deep?

The answer is very simple. In the first place, a sand layer acts as a natural drainage of the upper soil, and is very useful when excess water is present and definitely injurious where water supplies are rather small. The effect is more marked the nearer the sandy layer lies to the surface, since between—shall we say?—the loamy upper layer and the sandy layer a sharp break in moisture content quickly forms as the dry season sets in. Even when allowance is made for the fact (1) that plants cannot take up all the water present in soil, but only the excess over that quantity of water which is held by the finest particles of soil and is in equilibrium with the plant roots at the wilting point, and for the fact (2) that this excess (for a given moisture content (Trans.)) is less where the soil contains more clay, yet with the sequence of layers considered the amount of available water in the sandy layer falls below that of the upper loamy layer. Now roots spread but slightly or not at all from a moist to a drier layer of soil. As a consequence where loams overlie sand, if the difference in mechanical composition and other properties which affect the water economy of soil is reasonably big, one may observe that both below natural vegetation and below cultivated crops the main bulk of the roots comes to a stop, often as if cut off by a knife, at the sandy layer. This is penetrated by tap roots, but otherwise contains only such small dead residues of side roots

Matted Roots of Agave sisalana

as happened to develop there during the time that the sandy layer was soaked with water. In other words, every sandy subsoil below medium or heavy soils limits the root space for crops. On the physical side this limitation restricts the water supply, so that soils of this kind are very susceptible to dry periods, and on the chemical side it limits the plant foods to whatever may be present in the upper layer alone.

It was stated above that for crop plants about 18 inches of soil permanently above ground water level was essential. A layer of soil is thus permanently above ground water level only if it lies above the highest observable level of ground water, which is reached but a few times during the year and for a short time only, while for the rest of the year the zone of fluctuation is free from standing water to considerable depths and is accordingly well aerated. Under these conditions roots extend into the zone of fluctuation, whereas they do not penetrate into a sandy layer. It would therefore be wrong to draw the hasty conclusion that, since 18 inches of permanently drained soil generally suffice, 18 inches of soil overlying a sandy layer would also suffice. The requisite depth of soil for the upper layer is much more dependent on the root requirements of the crop grown, and this varies greatly with different crops.

All plants with tufty roots, and specially agaves (*see* Plate XI. sisal, the most important member of this class), have shallow spreading roots which are largely confined to the zone of soil between the surface and 30 inches depth. For gramineae and palms it is, as a rule, sufficient if there is 30-40 inches depth of upper soil above the sandy layer, unless periods of drought are to be feared.

The requirements of coffee are rather greater. For tea and cocoa five feet should be taken as minimum depth of soil, and even more in the case of rubber,

nowadays mostly *Hevea brasiliensis*, at any rate if the ground water-table lies very deep.

On many plantations there are areas of stunted growth which unmistakeably show the desirability and importance of paying attention to the presence of sandy layers when near the surface. On the other hand, where sandy layers of this kind occur there is the possibility that from time to time considerable quantities of water will be brought up to the zone of root development. This, however, is by no means the case when, instead of a light layer within the soil, there occurs a heavy illuvial horizon or where a relatively light upper layer overlies a layer of plastic clay. A definite hard pan of course forms a still more effective barrier. In such cases there is only a restricted space available for root development, and this zone is completely dependent for its water supply on what enters the soil from above, that is, on rain and possibly on surface run-off from adjacent areas. Water communication between root zone and subsoil is almost completely broken and, where the illuvial horizon or clay layer is not altogether too impermeable, is maintained for individual plants only by means of their tap roots, should they possess any. Since water can never move against gravity from the finer capillaries of the illuvial horizon to the wider capillaries of the upper soil, even a thin layer of this kind must make the upper soil a completely isolated system. It is obvious that under these conditions even more attention must be paid to the question of root space than where the subsoil layer is sandy.

These instructions are of course taken for granted by every farmer and belong to the A B C of applied soil science, which is not now our concern. I have, however, repeatedly had occasion to observe that time after time this same mistake is made in the tropics and subtropics, and have seen what huge

losses have sometimes been incurred by ignoring the presence of impermeable layers at a shallow depth. It is by no means rare for plantations to be laid out, without a word of criticism, partly or wholly on soils with not merely layers of impermeable clay but even solid beds of iron pan or actually solid rock some few inches below the surface. It is evident that the first dry season will make a clean sweep of the crop, and this often happens at an earlier stage, when there is an increase in the requirements of the growing plants for water and plant foods. In either case there is a total loss of all sums invested.

Salt horizons have the same practical effects as the layers we have been discussing, and the same point of view holds for them also. By way of summary it must again be said that **of all the considerations to be weighed in choosing soil a suitable conformation of the soil profile with reference to the behaviour of ground water is of paramount importance**, and to these conditions thorough attention should first be paid.

One often hears the view expressed that vigorous growth of trees or vigorous vegetation in general provides an unfailing guarantee that the profile is favourable for cultivated crops. It may indeed be that the advance of research in plant ecology will provide a series of indicator plants for use in this connection, but as a generalisation the opinion just quoted is entirely wrong, does not hold even for extreme cases and is particularly unreliable in the forest regions, where, during the protracted period of development, countless unknown factors have been at work, with the result that with uniform conditions of soil the plant cover may and probably does take on the most varied formations. Some reliance may be placed on the rule that a multivarietal tree cover, *i.e.* the association

of a number of deep-rooting and shallow-rooting growths, indicates a favourable soil profile of considerable depth. The lower growth is more significant in this inference than the tallest trees of the forest, since many of these giant trees have exceptionally shallow roots and are mainly supported by their buttress roots. Cases are not uncommon in which not only clay layers but also ominous sand layers lie a foot or so below primaeval forest. Especially suspicious is all cover consisting only of a few kinds of tree, and perhaps extending over enormous areas. Absence of undergrowth is a further bad sign, and under such conditions one must be prepared for unpleasant surprises in the matter of profile formation. For bush formations the same considerations, *mutatis mutandis*, apply. That grass and herb associations which have for the most part very shallow root systems give no information as to the deeper parts of the profile requires no special emphasis.

No soil should be taken up for agricultural development unless special care has been given to the examination of profiles.

This admittedly demands the expenditure of a great deal of work, but will bring a sure and notable reward. The practical procedure is very simple.

After one has obtained a general idea as to the probable manner of formation of the soils of a locality and also, if considered necessary, as to the nature of the parent rock, one should dig sample pits five feet deep in spots typical of the larger subdivisions of the area, which will as a rule be distinguished by differences in native vegetation. Recommendations are often made to the effect that sample pits should be regularly spaced on some rectangular or triangular system. This suggestion is hardly practical. For one thing, this procedure makes it unlikely that the pits will coincide with

the correct, *i.e.* typical, areas, and in the second place, if a careful choice is made of representative areas, one obtains the necessary data from the point of view of soil genetics with much fewer pits and accordingly with much smaller expense, and at the same time the reliability of the information is not impaired.

Profile samples are then carefully taken from the pits, and it is advantageous to take borings from the pit bottom to a depth of 10 feet, at any rate if deep-rooting crops are in view. Simple borings may then be interpolated at transitional points within the system of sample pits. To rely solely on borings is not advisable, in spite of the fact that this method has been frequently employed in practice. The boring tool so greatly disturbs the layers and horizons that, although an experienced investigator can identify them from the contents of the auger, the non-specialist is liable to considerable errors.

If the sample pits and bore-holes have been well sited from a soil genetics point of view, a very small number is, as a rule, sufficient to give the enquirer a good representation of general soil conditions which can be utilised at once and with confidence in drawing up a scheme of cultivation. Thus, knowledge of the main profiles which are related to vegetation locally, and can in fact be widely generalised, shows forthwith where one can plant deep-rooting crops with success and where not, and shows also in what places one may expect difficulties from ground water, and in what places periods of drought will prove dangerous. Even if one limits the examination of the horizons to visual inspection, and has but the slightest acquaintance with soil science, one obtains in this way a definitely useful conception not only of the profile formation but also of the physical properties of the soil, more particularly the greater or less degree of heaviness at the various

points and for the separate horizons. This constitutes a further guide for the choice of a particular crop, or for the suitability of the soils for the crop which it is intended to plant.

Plants which require specially well-aerated soil will not be put on heavy clay or on soils in which the clay content increases sharply in the subsoil, and conversely, plants which prefer heavy soil will not be put out on light sand. It may, however, be noted here that in the tropics and subtropics, with their magnified climatic influences, a factor enters which has a very limited effect in temperate climates. In the tropics thorough cultivation and, to a greater degree, draining transform even the heaviest soils to much lighter ones often in a surprisingly short space of time. The result is that, with the possible exception of heavy clays low in humus, practically any crop can be grown with success by good management of the soil, provided that its chemical properties are suitable. The necessary cultural operations naturally entail a heavy outlay on labour, so that it is usually preferable to adapt the system of cropping from the start to the local peculiarities of the soil or to cut out areas which are not altogether suitable. In opposition to this plan one often hears the contention that it usually gives an untidy look to a plantation. This argument cannot be considered valid in view of the indisputable fact that a plantation is a commercial enterprise and not a beauty parlour. It must be borne in mind that an unsuitable area requires in the end as much, and usually more, cultivation than the good soil, and since the costs of cultivation are at least as high, its yields, which are often much lower, may sometimes very markedly pull down the total profits.

With regard to the physical properties of the soils, it is strongly recommended that at any rate the

chief representative profile samples should be submitted for thorough investigation by an institute familiar with the examination of tropical soils. The expense involved is amply repaid, since appropriate investigation always provides useful guides on the physical management of the soil, whereas simple inspection, though backed by the greatest experience of soil science, cannot reveal the information required. How suitable samples are to be procured will be stated below in connection with the chemical aspect of soil selection. From the physical point of view the data to be obtained are as follows:

(1) The mechanical composition of the soil expressed on Atterberg's international scale. This permits immediate comparison with other soils of similar districts.

(2) All the data which characterise the behaviour of the soil to water and air. These should be sufficient for drawing up an approximate balance-sheet for water and air during rainy and dry seasons. For this purpose it is necessary to determine the weight of a known volume of soil in its natural condition. From this the distribution of water and air among the solid particles may be ascertained with sufficient accuracy when the specific gravity of the soil material and its shrinkage coefficient are known. It is necessary to determine also the capacity of the soil for holding water, and one or other of the factors which make possible an approximate estimation of the wilting coefficient of the soil. This is needed, since the only water of practical use to the plants is that which is in excess of the wilting coefficient; this is water in excess of that amount so firmly held by the soil that plants can no longer withdraw any. In different countries different measurements are used for determining this value: Mitscherlich's hygroscopicity, the coefficient of hygroscopicity and so forth. Direct determinations

of wilting-point are seldom made nowadays. This characteristic is a fundamental value of very special importance. No other criterion brings out such surprising aspects of the soil in figures which throw light on the whole problem of cultivation. There is, for example, a large number of heavy tropical soils in which the wilting-points are so high that only when in the form of mud do the soils give up water to the plant. It is clear that with such "physiologically dry" soils injury from drought may appear more rapidly than with apparently dry sands, although the heavy soils are apparently still moist or even wet. Such behaviour would seem inexplicable to the planter who judges by appearances only. A clay soil containing 60-70 per cent water has, if its wilting-point is of this magnitude, a greater tendency towards drought than a light loam containing perhaps only 19 per cent water but having a wilting-point of about 2 per cent. From the practical point of view it is evidently important to have this information prior to cultivation.

Other things being equal, the more available water there is present in a soil of the hot climates the greater will its value be. This results from the fact that throughout, even in tropical areas of heavy rainfall, water with very few exceptions is the limiting factor in Liebig's sense, that is, water determines the level of production. The renowned fertility of the Dutch East Indies is, in many parts of the country, no consequence of a special fertility of the soil. Admittedly the volcanic soils are often rich, but even so they do not compare in this respect with many soils of the dry regions, as must be clear from what has been said already. In the great majority of cases the high yields are a consequence of the greater amounts of water naturally available for the plants or made available by good methods of cultivation. It is worthy of note that the admir-

ably conducted research stations of the Dutch East Indies, after decades of experiment, regard as a minimum figure for this soil property 400 cubic metres of available water per hectare and per 10 cm. depth of soil, where this is of good quality and where rain is ample.[1] Even in the Indies, where rainfall is very heavy, the amount of available water is below this minimum in more than 60 per cent of the cultivated areas.

For low-lying soils measurements of permeability are obviously of pre-eminent importance, but it must be noted that laboratory determinations of this property are still very uncertain and also that it is a matter of great difficulty to remedy defective permeability.

Reliable measurements as to ease of cultivation can only be made in the field, although a fairly correct indication of this property can be obtained from the estimations mentioned above.

Apart from profile structure, vegetation has been used for evaluating the physical properties of soil. There is indeed a fairly close connection between vegetation and physical properties when, by means of observation on the spot, it is possible to establish a local correspondence as basis of the evaluation. Both plant associations and individual plants may serve as indicators for heavy and light soils, for well aerated and badly aerated soils and for soils with good or bad provision of water.

In forest regions it must be noted again that undergrowth rather than giant trees is the safer guide. In particular, certain kinds of palm, such as Rattan cane palm [*calamus sp.*], Nipa [*Nipa fruticans*], etc., indicate heavy, badly aerated soils. Much has still to be learned, however, on this subject owing to the great variety of tropical forest flora. In drier districts a cover of thornless forest

[1] Roughly equivalent to 500 m³ per acre per foot depth of soil.

or scrub makes a fairly regular appearance on the lighter kinds of soil. Tall sour grass[1] is to be found, as a rule, only on the heaviest clays; other grasses of tall or low habit may grow on the most varied kinds of soil, so that no general rule can be given. For limited areas which have uniform climatic conditions the connection between plant associations and physical properties of the soil is almost mathematically exact, and can even be used as the basis for accurate map-making when a careful study has been made of the physical properties of soil below the typical plant formations of a locality.

The chemical properties of soil can be ascertained only with the greatest difficulty, if at all, in default of technical investigation in the laboratory. In this respect recourse to vegetation as a basis for evaluation is particularly misleading. The reference is to native vegetation—cultivated plants are not considered, since they can serve as a reliable guide only after a long period of growth. Apart from typical salt plants, such as salt bush and tamarisk, which usually, but by no means always, indicate that the soil contains more salt than any crop plant can tolerate, I could not name a single plant or plant association which, with even moderate reliability, indicates certain chemical properties of the soil throughout the tropics and subtropics. This does not mean of course that one cannot, on the basis of trials made for this end in one locality, find out certain plants and plant associations which serve as indicators and then make successful use of them for evaluating soil. The only restriction is that observations of this sort can never be of general use, since at a distance of 50 miles they may be entirely misleading. In this respect by far the least reliable indicator is the dense forest of the tropics and subtropics, which is often hailed as a

[1] Hard grass of little feeding value.

sign of very rich soil. To make this clear one needs merely to consider the conditions under which the forest has grown. It has been standing for thousands of years. For thousands of years the roots have brought up plant foods, often from deep-lying zones of the subsoil, and these plant foods are continually returned to the soil surface by falling leaves or other residues, and after decomposition of the residues again become available for the roots. In this way below all forest cover there is gradually established a condition of permanence which has really nothing to do with the soil itself. From the chemical point of view the soil is simply providing a foothold. The forest provides its own food requirements in a cyclic process of growth and decay. When this cyclic process is disturbed by felling and cultivation, all forest soils show a moderate or even great fertility for a comparatively small number of years, in fact for so long a time as reserves remain in the surface layers, and particularly in the humus layer. Fertility is maintained only until these reserves are used up, and even in the best forest soils they are by no means great. For a period which does not exceed three or four years, as a rule, the cultivated plants thrive and exhaust a capital of plant foods which took thousands of years to build up, and which receives no addition after the felling of the forest. If the soil itself is rich, all goes well thereafter. But since the tropical forest is largely self-supporting, even the most vigorous stand is no guarantee that this will be the case. The soil may indeed be extremely poor, since after continuous development during thousands of years the rank growth is practically independent of the soil. With forest soils of this kind the crop is suddenly overtaken by a disaster which seems unbelievable to the planter, but which is intelligible enough from the conditions here described. The

plants, well supplied with food at first and possessing well-developed root systems and stems, come practically to nothing. The vigorous early growth ceases, leaves and twigs fall off, often, especially in the case of coffee, even the first crop does not develop or is irregular, and a swarm of animal and vegetable parasites spreads over the weakened plants in a terribly short time. One does not need to have seen many plantations to have met instances of such calamities, which are, for the most part, ascribed to quite other causes than negligence and lack of thought in the choice of land.

There is no need to emphasise that a sparse cover gives even less information about the chemical properties of the soil than does dense forest.

In nothing must the agricultural pioneer seeking land be more cautious than in estimating the richness of soil by vegetation alone. No circumstance has entailed so many agricultural blunders as has neglect of care in this respect. Only the most conscientious investigation of the soil itself can guard against such mistakes and their grave consequences to the farmer.

The planter himself can make only a very partial and preliminary investigation, and will be well advised to leave the greater part of the work to laboratories or research stations equipped for the purpose. Of recent years certain soil workers, knowing little chemistry, which should form the scientific basis of their subject, have fostered a tendency to make every farmer his own soil chemist by means of simple and rapid tests. It is suggested that he should be able to determine for himself not only the important soil reaction but also phosphoric acid and so forth. A few lines of printed instructions seemingly place at his disposal the whole body of knowledge which no research station would claim to possess even after many years of

assiduous study. In the interests of all farmers in the tropics and subtropics **an urgent warning must be given against this irresponsible pseudoscience.** These rapid methods of chemical examination, which appear simple and are indeed often of great value, require careful handling and wide knowledge of the difficulties of estimation and sources of error occurring at every single stage of the determinations. In default of this they may give false results, and can be used with any prospect of success only in special laboratories and by specially practised investigators. The isolated pioneer farmer will, as a rule, have neither the apparatus which is essential for obtaining reliable results, nor the still more necessary special knowledge of chemistry. He will be wise therefore to limit himself to those observations that he can make for himself without danger of grave error.

The first of such observations is to ascertain fairly correctly the nature of the parent rock of the soil, if such rock be anywhere exposed. A small collection of rock specimens for comparison is very useful for this purpose, and may be purchased cheaply in a reliable form. Simply to know the main type of parent rock or rocks gives a very valuable idea as to what may reasonably be expected of the soil. Rich soil is indicated by all volcanic rocks, and particularly so by the basic volcanic rocks which are mostly dark. Amphibolite and biotite gneisses usually yield good soils, as do also granites containing much dark material. Reference may be made to earlier remarks on this subject. A moderate acquaintance with minerals makes it possible to determine the most important mineral residues in a soil by means of a simple technique which has already been described in detail. It is clear that a soil will be better, that is, the probability, though not the certainty, of richness in respect to plant foods will be higher,

the more mineral reserves it contains. If quartz and acid glass are excluded, 1-5 per cent primary minerals for clay soils, 6-15 per cent for loams and over 15 per cent for sandy soils may be considered high. Attention has already been drawn to the importance of fresh rock fragments in soil and, on the other hand, to the importance of secondary concretions as a mark of age.

A second observation of evident importance which can be made on the spot is to note the presence or absence of an appreciably high content of humus. In this one has to guard against errors due to iron compounds. In hot climates a soil rich in humus is to be preferred to one low in humus, since it contains rather more nitrogen and probably more phosphorus also.

It is hardly worth while, and even misleading, to apply the test, so valuable in temperate climates, of seeing whether the soil effervesces when treated with hydrochloric or other acid, and so determining whether calcium carbonate is present in considerable amount. In the humid tropics and subtropics the majority of soils will not respond to this test, since calcium either does not occur in the form of carbonate or may be present in traces only. Such soils may nevertheless contain far too much calcium for many crops. In hot dry climates, on the other hand, it is difficult to find a soil that does not respond to the test, that is, which does not effervesce when treated with acid. Nevertheless many such soils require addition of calcium, though not in the form of calcium carbonate, not in spite of the effervescence but because of it, for in them the effervescence may be caused by alkali carbonates.

It follows from this that soil reaction, which in temperate climates is best modified by liming, is to be considered from quite a different view-point in hot climates. The difference is accentuated by

the circumstance that many tropical crops have rather narrow optima of soil reaction, and these may lie at some distance from the neutral point. The optima can, however, be correctly ascertained only from the total composition of the plant foods in the soil, and this is finally expressed in the soil reaction. A mere determination of soil reaction means even less in hot than in temperate climates, where it may indicate need for liming, although the amount required may not be clearly shown. There is accordingly no point in taking great pains to determine soil reaction on the spot unless a complete analysis of the soil is available. This can be carried out only in a technical laboratory, and it is greatly in the interest of the planter that this should be done.

On the assumption that a mineralogical analysis has already given information as to the reserves of a soil, the first task of a complete analysis will be to determine the total exchangeable bases, that is, the bases held by sorbtion. This should include determination of adsorbed hydrogen ion (residual acidity) and of aluminium ion (exchangeable acidity). Furthermore, in addition to determining the degree of saturation, *i.e.* the total percentage of bases held by the sorbtion complexes, it is necessary to ascertain the detailed make up of the bases, since it is not merely a question of absolute amounts of plant food (provided these exceed a certain minimum level in the soil, and this is usually the case), but rather of the relative proportions in which the different bases are present. The latter factor determines what can and what cannot be taken up by the plant roots. It is not possible to enter here into further details of the extremely complicated relations that have to be considered when evaluating the plant food content of a particular soil, since this would greatly exceed the

scope of this book as a comprehensive survey of the framework of soil science. An example drawn from tropical practice will, however, amply illustrate how the matter lies.

Two light sandy loams, hardly distinguishable by eye, both formerly under heavy tropical forest and both having about the same reaction of *p*H 5·2 to 5·5 (this being optimal for tea), gave the following figures for composition of their exchangeable bases:

ABSOLUTE FIGURES IN MILLIGRAMME EQUIVALENTS PER 100 C.CM. SOIL

	Ca	Mg	K	Na	NH_4	Al	H	P_2O_5 (mg.)
Soil 1 . .	8·8	1·3	4·4	0·7	2·0	0·2	4·8	11·7
Soil 2 . .	3·2	0·3	4·1	17·6	0·3	?	2·0	14·5

It will be seen that if the analysis were limited to determining the important plant foods, as is unfortunately the case in most countries, with the exception of the Dutch East Indies, the conclusion would be that, except for rather higher phosphorus content of Soil 2, the two soils are fairly level in respect to potassium and differ only in that calcium is rather lower in Soil 2. One would be in doubt as to whether this difference was of any practical importance, and in absence of a total analysis would be led to the conclusion that the two soils would show much the same behaviour under cultivation, and that the second would perhaps be the better in virtue of its higher content of phosphoric acid. In point of fact, however, Soil 1 from the Dutch East Indies holds the world's record for tea, and for one hundred years without a break has produced the highest yield and the best quality, whereas Soil 2, which is not very distant from it, produces practically nothing at all. The reason is quite evident if one considers the solubility relations of the bases in the soil as determined by

complete analysis, and by this alone, for complete analysis is simply indispensable for thorough valuation of soil. The following percentage figures give the proportions of the bases:

	Ca	Mg	K	Na	NH_4
Soil 1	51·2	7·5	25·6	3·7	12·0
Soil 2	12·5	1·2	16·0	69·0	1·3

Whereas in the first complex the various bases and, in particular, monovalent and divalent bases are well balanced, in the second case the extremely high content of sodium, which is usually not determined at all, completely disturbs the "harmony of plant foods", to use Nolte's phrase. The firmness with which the various ions are held is such that, in the case of the second soil, the plants can obtain practically nothing except sodium. In addition to this, the sodium content is so high that when the soil is moistened it becomes a soapy mud.

So striking a case is certainly unusual, but similar examples are by no means rare, and, except for complete colloid-chemical analysis, there is no means of recognising and avoiding them or seeing how the difficulties may be overcome.

The desirability of determining phosphoric acid and its degree of solubility has of late been recognised for soil valuation even in temperate climates. It is specially desirable in the development of tropical and subtropical areas in which a low level of phosphoric acid, with the attendant necessity of manuring with phosphate where transport is difficult, may become a weighty argument against bringing a soil into cultivation. It is to be noted that phosphoric acid figures for tropical soils have to be considered on a basis differing from that used for temperate soils. In hot climates the availability of phosphoric acid as of other plant foods is higher. As a general rule a soil that contains per 100 c.cm. 10-12 mg. phosphoric acid soluble in 2 per cent

citric acid and 30-40 mg. total phosphoric acid, will not need manuring with phosphate for a considerable number of years. Total phosphoric acid is here used in its literal sense, and is not to be confused with acid-soluble phosphoric acid, which is usually determined instead.

Limiting values for other plant foods can hardly be given in a form which the practical farmer can use, since, as was explained above, the behaviour of the soil depends not so much on the absolute amounts of the bases as on the proportions in which they are present. Every soil has to be treated as a separate case, and this can be done only by an institute which is accustomed to examining tropical soils, unless the planter himself has many years of experience in estimating the productivity of soils. **It cannot be too strongly emphasised that before one decides upon the choice of a soil one should arrange for a chemical examination, either with a view to its general fertility or with respect to its suitability for some particular crop.**

The way in which soil samples are taken will depend on whether the objective is to obtain an estimate for an area of soil as a whole or to determine special questions as to plant foods and suitability for separate parts of an area. In the first case, the following procedure is to be recommended: without disturbing the natural binding and structure of the soil, cut from the side of the sample pit by means of a sharp spade or knife, a lump of soil not less than 12 inches deep and so shaped as to fit fairly closely into an ordinary biscuit tin. The tin is immediately soldered up and is then ready for dispatch. If the soil shows no profile one proceeds in exactly the same way to take samples representing the soil-layers from 20-32 and from 48-60 inches depth, so that each sample pit provides three

samples, each of which should be carefully described in respect to layering, colour and so forth in notes sent with the samples. An ordinary biscuit tin holds about 4 lbs. fresh soil, which should not of course be compressed, since that would largely destroy its natural structure. This quantity is quite sufficient for the necessary physical and chemical tests of the laboratory. The more care that is given to taking the samples without disturbing the structure and to making notes, even as to minute and seemingly trivial details observed on the spot, the more valuable will the analysis be, and practical conclusions based on the analysis will have a proportionately wider scope.

If the soil shows a profile, it is of course necessary to make a scale drawing of the whole and to take a sample from each horizon down to a depth of five feet, or down to solid rock,a sample of which should also be secured.

Except for mountainous districts soils are reasonably uniform, so that if sample pits are sited with careful regard to the conditions under which the soils were formed, quite a large area may be adequately sampled by means of a small number of pits. The investigation accordingly requires an outlay which is very small in relation to the value of the information obtained.

A quite different procedure is to be followed in soil sampling when it is desired to characterise a soil for its suitability for a certain crop or to estimate its probable manurial requirements. In these circumstances one should adopt the European practice of obtaining a composite sample for the top 12 inches of soil, and another for the subsoil between 20-32 inches. This is most conveniently done by means of a boring tool. To begin with, one divides off areas which, from the appearance of the soil and from the stand of vegetation,

appear to be uniform. From each uniform area, presuming the general nature of the profile to be already ascertained, small surface and subsoil samples are taken by the borer from about 50 points regularly spaced within the piece of land. The surface and subsoil samples are then composited by mixing the material as carefully as is practicable and then taking a fair average sample from it. This should amount to about 4 lbs. and should be soldered ready for dispatch. One should try to do the compositing without allowing the soil to dry out, unless of course the material is dry when first taken. The soldering is necessary because the majority of tropical soils, and especially those from the moist tropics, change so extensively on drying out that data obtained for the dried material are not altogether reliable.

As a rule every field of considerable size thus provides one composite surface sample and one composite subsoil sample, so that in this case also, although a good deal of work is involved, the cost of investigation alone does not become large, since the number of samples for examination is usually very small. It is worth while to submit along with a batch of composite samples an additional sample showing the natural soil structure for the guidance of the investigator. One should send also a very detailed description of the samples, and make a point of noting carefully the native vegetation or the appearance and yield of crops growing on the piece of land which has been sampled.

When soil samples have been carefully taken in this way every modern agricultural institute in the tropics is now able to obtain, by investigation, so just a view as to the properties of a soil that errors in the choice of land can be avoided, and, in addition, valuable practical suggestions may be obtained as to the choice of a suitable crop and

as to the technical management of the soil from chemical and physical view-points. The limits of this book do not permit a detailed account, and a short indication of the most important points must therefore suffice.

CHAPTER VII

PHYSICAL ASPECTS OF THE CHOICE OF CROPS AND SOIL MANAGEMENT

IT has already been noted that, from a physical point of view, the factor which demands most careful consideration when choosing soil for a crop, or vice versa, is the provision of sufficient room for root development. Ample root room or, in general, ample space for the plants is primarily of importance in the water supply of the crop, a point which has usually been treated by novices in tropical agriculture with a noticeable but hardly appropriate lack of precision. If one enquires why a particular crop, or why a system of crop spacing, has been adopted for some plantation, one usually learns that the choice was made because it "did well" somewhere else. Further questions as to whether the rainfall is sufficient for this crop and for the number of trees planted per acre, or as to whether the system of cultivation rests on any estimate as to the requirements of the crop in that locality, usually demonstrate that the planter in question has no idea of the actual water requirement of his crop and has planned his lay-out on guesswork.

Although there is a lack of detailed data based on researches into the water consumption of crop plants, it is certainly possible to obtain an estimate which is quite sufficient for practical ends. On the

whole, tropical and subtropical crops consume about 400 units of water per unit of dry plant substance. This dry substance is not of course the yield, but the total growth made by the plants during the year, and is to be reckoned as a multiple of the yield. Similar considerations hold for any green manures that may be sown, or for the weeds that grow between the cultivated plants. At the spacings which usually give the highest yields the water consumption of the most important crop plants are somewhat as follows, the figures being expressed as millimetres of rain:

Cereals	120-150	Oil palms	600-700
Maize and millet	200-250	Agaves	200-250
Sugar beet	400-500	Coffee	250-300
Tubers and roots	300-400	Cocoa tree	300-400
Oil seeds	120-150	Tea	350-400
Hemp and jute	200-250	Vines	100-150
Cotton	200-250	Fruit trees	100-200
Cocoanut palms	200-250		

These water requirements seem extremely low, but here also appearances are deceptive. They are in fact very high, for on the average they have all to be multiplied by five, since little more than 20 per cent of the rain is really used by the plants owing to losses by evaporation when rain falls on the plants, and to further losses by deep penetration. This estimate, based on theory, amply confirms the practical experience of the Dutch East Indies that even where rainfall is extremely heavy water is but rarely available in excess of the requirements of cultivated plants. The first task of the practical planter who wishes to obtain the highest possible yields is to devote most careful attention to maintaining the moisture content of his soil and ensuring penetration of every drop of water that falls on the land or is led to it by irrigation. This is of course specially important

in areas where rainfall is rather low. One of the first measures to be taken for this purpose is to restrict the number of plants per acre in relation to the amount of water provided, so that each plant has a chance to reach its maximum development. When water is rather short it is much better to plant at wider intervals and, by making a good mulch between the rows, give fewer plants good conditions for growth than to plant more closely and obtain a uniformly stunted crop. It must be noted, however, that possibilities in this direction are, as would be expected, not very extensive. Direct methods of rational soil management directed to conservation of moisture are, however, of great value.

Attention has already been drawn to the fact that, owing to the high density of rainfall in the tropics and subtropics, every slope is likely to receive less than its fair share of water. There is, in addition, grave danger of erosion, which may remove great quantities of the valuable topmost soil in which humus is present. For this reason the first task of good farming is the terracing of all slopes for prevention of water loss and erosion (*see* Plate XII).

The second consideration of quite general importance is increasing the water-holding capacity of a soil to a maximum by obtaining the highest possible degree of good tilth within the zone of root development. For annual plants this can be done by thorough working of the soil to a good depth, but the method employed must be well suited to the soil in question. Heavy soils as a rule respond very well to deep cultivation in the ordinary sense, *i.e.* to deep ploughing or cultivation by hand, since this often has a surprisingly big effect in increasing their ability to yield water to the plant although their water-holding capacity

PLATE XII

TERRACED RICE-FIELDS

is not appreciably impaired. With light soils, on the other hand, this procedure is highly dangerous. Here, in contrast to the clays, the colloidal constituents of the soil, which are not in any case present in large amount, are coagulated by deep cultivation or even destroyed, with the result that a light soil thus treated rapidly loses all power of retaining water. In such cases shallow ploughing or hand-working must be accompanied by simple loosening of the subsoil, so carried out as to avoid carrying down the surface soil to great depths. All operations comprised under the head of dry farming must be judiciously employed so long as the fields are bare of crop.

For crops of perennial growth really deep cultivation of the soil is obviously desirable, and this should include the preparation of deep broad pits for the single plants. When the crop is once on the field, however, a narrow limit is set to soil cultivation owing to the necessity for avoiding injury to the roots, and the deeper layers of soil are accordingly then out of reach. It is happily the case, however, that **in the extensive use of green manures we have an admirable means of improving the texture of the subsoil down to considerable depths.** At the same time, in spite of the apparent paradox, large quantities of water are conserved for the main crop. This is always possible if one chooses for green manuring a plant which occupies for its main root development a different zone of soil from that required by the main crop. More than eighty kinds of green manures are known, and for any locality there will be quite a number of these that can be used with advantage. They should be sown at the beginning of the rainy season, so that they will reach their full development during the wet period when there is a certain excess of water in the soil. During this time they will not make any

inroads upon the water supply of the main crop, since, although the green manure itself uses up some water, it effects an equivalent economy by shading the soil surface in between the rows and at the same time keeps the weeds down. When the dry season begins, the green manure crop must be harvested and spread between the plant rows. This provides an inert soil cover which very materially reduces evaporation from the soil surface, apart from conferring other benefits to which reference will be made later. The excellent results of this operation may be plainly seen at any spot where plant residues cover the soil, for whereas at a distance of a few feet the soil is dried out to a considerable depth, the soil below a layer of residues remains moist even in an arid climate, and possesses in addition an excellent tilth which is not to be attained by any other means. Increases in water-holding capacity of the order of 10 or 20 per cent, brought about by well-considered green manuring, may be readily demonstrated by analysis in the case of soils so treated.

During dry seasons, if these are at all pronounced, the soil between the rows of a well-managed plantation should never be without a dead cover. There is no more effective means of conserving soil moisture, and the labour expended on this operation is many times repaid, since a cover of this kind largely restricts the growth of weeds, and outlay on green manures may accordingly be reckoned as a direct saving in the cost of keeping the land clean. An even more effective means of reducing evaporation and growth of weeds consists in spreading special covering material, sheets of cardboard and so forth, between the plant rows, as is done on a large scale in Hawaii and the Philippine Islands. This method of course is costly, and can only be used in the case of valuable crops such as

pineapples, and where agricultural conditions are most favourable.

Where use of a deep-rooting green manure fails to bring about a good physical condition in a heavy and impermeable subsoil, or where the improvement seems to be too slow, it is advisable to dig aeration pits of corresponding depth and to keep them open, throwing in all organic waste obtained when the crops are taken, or at other times. In the course of the year the pits are changed from row to row. Experience has shown that a good and lasting result may thus be obtained on heavy soils, but a good deal of work is of course required.

Attention has already been drawn to the extreme importance of adequate drainage, and it is not necessary to enter into detailed discussion on this point. It may be remarked, however, that the matter is of special moment in the case of all irrigated soils which are in danger of becoming too salty, and that means practically all soils of the hot regions. Of this danger Egypt provides an example of the first magnitude, for there rise of the water-table accompanied by rise of the salt horizons caused damage which is difficult to estimate, although remedial measures alone must have cost round about twenty million pounds.

CHAPTER VIII

CHEMICAL ASPECTS OF THE CHOICE OF CROPS AND SOIL MANAGEMENT

We have seen that soil reaction is the product of, and represents the sum of the chemical conditions of any soil. Plants are children of the soil on which they stand, and it follows that every plant, or rather every kind of plant, is adapted to a certain range of soil reaction. The reason for this is not that reaction is in itself of importance, but because it is a composite value characterising the general level of plant foods in the soil.

Acid reactions generally indicate that plant foods become available rather slowly and that the soil solution so formed is dilute: alkaline reactions indicate the reverse. Phosphoric acid is excluded from this generalisation, since it is an anion and behaves in a different way. The fact that plants are fairly tolerant in respect to their nutritional requirements, and the possibility that, where physical conditions for growth and, in particular, where there is ample supply of water, unsatisfactory chemical conditions will be largely overcome, leads to the conclusion that all plants possess a fairly wide range of tolerance in respect to soil reaction. At the same time, for any given climate each kind of plant displays within this range an optimum which varies a little with place and with

local conditions, but nevertheless has fairly narrow limits.

Application of lime or alkali carbonate, possibly in the form of wood ashes, provides a means of changing soil reaction towards the alkaline side, at any rate within the root zone. There is no practical possibility of modifying a too acid subsoil carrying deep-rooting perennial crops. Artificial acidification by means of sulphur and so forth is an easier proposition, since these materials can be made to act through considerable depths of soil. All these operations, however, cost money no matter how effective they may be, so that even under the most favourable conditions they become a charge on the profits of the estate. It is much preferable to choose a soil where they are not needed, that is, to choose a soil with the reaction preferred by the crop, or vice versa.

Unfortunately information as to the requirements of crops in respect to soil reaction is not complete, but certain valuable observations have been made and are well worth attention. The upper limit of soil reaction lies at about *p*H 9 for practically all crops. Soils which exceed this figure, whether much or little, are definite alkali soils with an appreciable content of alkali carbonate. Such soils cannot be cultivated with success unless previously treated with gypsum, and then thoroughly leached by large quantities of irrigation water. Where the lower limit of soil reaction for plant life lies cannot yet be stated. In contrast to the upper limit, which is no rarity in dry regions, the lower limit is to be met only in very exceptional cases. The following plants prefer alkaline reactions, that is, soils with a *p*H value exceeding 7:

Grain crops	Hemp and jute	Agaves
Oil seeds	Cotton	Vines

Plants with the optimum in the neighbourhood of the neutral point are the following:

Maize and millet	Tobacco	Cocoa tree
Sugar beet	Cocoanut palm	Fruit trees
Tubers and roots	Coffee	

A slightly acid to acid reaction is favoured by oil palms, which are very tolerant to acid conditions, and the same is true in a marked degree of tea, which is very susceptible to lime and alkalies.

The rubber tree, *Hevea brasiliensis*, apparently grows over the whole range of soil reactions and has no well-marked optimum.

The plant food requirements of tropical and subtropical crops have been approximately ascertained in the case of annuals or crops which are removed as a whole from the field. For the most important varieties the figures (pounds per acre) lie within the following limits:

	Nitrogen	Phosphoric Acid	Potassium
Grain crops	60-70	25-30	70-80
Maize and millet	100-120	50-60	125-150
Tubers	50-70	25-30	100-150
Leguminosae	(200-250)	60-80	100-200
Cotton	60-90	30-40	60-80
Tobacco	110-130	15-25	120-150
Sugar beet	100-125	70-90	200-250
Pineapples	140-170	40-60	300-350

Requirements for calcium are not included in this table.

In the case of perennial crops figures are certainly available for the amount of material removed in harvesting, but these are not of much use, for although prunings are returned to the soil the living stem and root system locks up a very considerable quantity of plant food, and this should be reckoned as material withdrawn from

the soil. How large an amount is thus withdrawn is not at present known even approximately. In general one will hardly err in estimating consumption by trees at about 50-75 lbs. phosphoric acid, 70-100 lbs. nitrogen and 100-150 lbs. potassium. The requirements of oil palms are no doubt higher in view of their great bulk. Agaves require at least as much as is here estimated for trees, and probably require even more potassium, for, contrary to current opinion, they take a good deal out of the soil.

At the present time there is a decided change of opinion on the question as to how the quantities of foodstuffs in the soil are enabled to supply these requirements.

On the one hand, it can hardly be doubted any longer that results obtained in lysimeter studies greatly overestimate the amount of material leached from the soil by rain. Quite considerable quantities of plant foods are no doubt lost in this way every year, at any rate in a wet tropical climate, and especially where artificial drainage has been installed. They are, however, assuredly less than the results which one is bound to obtain from a lysimeter which is artificially enclosed and drained. In drier climates the losses will be small unless irrigation and drainage are introduced, and may at times be changed to increases by accession from the subsoil.

On the other hand, recent investigations into the mobility of plant foods in soil are opening up quite new points of view which are of far-reaching practical importance in the estimation of soil richness and the degrees to which that richness can be exploited. Until quite lately the general view was that plants derived their nutriment from the soil solution alone, and it was implicitly assumed that the soil solution was fairly uniformly distributed

through the soil, and that loss of plant food at one place was made good by some adjacent portion of soil. The only tenable section of this theory is that the plant actually takes up only dissolved nutriments. There is no question of distribution through the soil unless a stream of water moves through it, and that is only exceptionally the case within the root zone, as when either rain soaks into the soil or the ground water-table rises. Lateral movement is extremely rare, and there is only a very slow rise or fall of the plant foods. The soil is by no means uniformly permeated with dissolved or readily soluble nutrients, but is a mosaic of richer and poorer particles towards which the plant root grows, and then actively takes its nutriment on the spot from the water film surrounding the particles by displacing, by means of the ions it liberates, substances which were held by the particle.

In the same way one must not assume that plant foods brought on to the soil will be evenly distributed: the heavier the soil the more likely is it that the added substances will be retained by the surface layers, so that unless enormous quantities are applied it may be a very long time before the dressing has any effect on deep-rooting crops, and it may indeed fail entirely. When a dressing is applied the amount fixed by the soil and the amount remaining in solution, and therefore of immediate effect, depend entirely on the sorbtive behaviour of the soil in question, and this can be determined only by complete colloid chemical analysis. Any generalisation on this subject would be misleading.

It may be noted that the extent to which a plant can remove foodstuffs from the soil finally depends on the development of the root system, which grows from drier and poorer spots to the richer and wetter ones which act as stimuli. It

is desirable that the root should obtain what it needs with the least possible expenditure of energy, since this is used up at the expense of aerial development. Ample foodstuffs will of course be most easily obtained when they are present in large amount and are well distributed through the soil. From these platitudes follow consequences which are still often overlooked in practice.

It is clear, in the first place, that, since the plant has but a limited space in which to throw out roots, even the richest soil will rapidly become poorer as successive crops are taken away. The depletion will not be general but will occur in respect to particular plant foods. It follows that **unless fertilisers are applied to the soil no tropical crop can for long continue to give high yields.** How long it will be before manures are needed depends on the extent to which the soil contains reserves of plant foods, that is, on the richness of its mineral reserves and the rapidity with which they break down. In view of the fact that the subsoil on which all tropical and subtropical perennial crops largely rely is pretty well beyond the reach of fertilising agents, very particular attention should be paid to securing a subsoil which is amply supplied with plant food. This is more important in the tropics than in temperate regions, and it is of course desirable to study especially those substances which are removed in large amount by the crop concerned, or those which are very readily taken up by the soil and are therefore difficult to distribute evenly.

Phosphoric acid is the most important example of the latter group. In soluble form it is found only in soils of low sorbtion capacity. Application to any strongly sorbtive red earth is necessarily futile, since the phosphorus will usually be completely fixed in a few inches depth of soil. On such soils it is better to apply a larger dressing of the cheaper

finely ground raw phosphate, which should be worked into the soil as deeply as is practicable. Red loams are, as a rule, less troublesome.

The fact that most crop plants of the tropics require large amounts of potassium makes it clear that in the humid tropics special attention should be given to the supply of available potassium in the soil. This is specially important in the case of all soils in which the sorbtion complexes contain large amounts of sodium, and this consideration holds also for soils of drier climates. In the dry regions, however, there is the possibility that some reserves will be brought up from the subsoil during the dry season.

Practically all soils of the tropics and subtropics need nitrogen in order to give maximal yields.

Deficiency of lime occurs only in the most acid soils or for crops such as the agaves and hemps, which have a marked preference for calcareous soils. On soils which are salty without being definitely alkaline, calcium may be required for balancing the sorbtion complex, and it may also be of value in improving the physical condition of very heavy clays. In the latter case calcium must be applied as carbonate or as gypsum, according to circumstances.

It thus appears that, if one aims at high yields and not simply at yields dependent on the residual production of plant foods by the soil, even the best soils require manuring in the tropics as in temperate climates. Without application of manure satisfactory yields are obtained only from exceptionally rich soils such as the Indian *regur*. On the other hand, in agricultural undertakings of the tropics and subtropics application of plant foods derived from an external source can be cut down to a far greater degree than is possible in temperate regions by making full use of green manuring.

We have already remarked upon the great value of green manures for improving the physical condition of the soil; their value from the chemical side is even greater. Plants chosen for green manuring remove large quantities of nitrogen from the air if the nodule bacteria on which their growth depends are either present in the soil or are added artificially. With good cultivation these amounts of nitrogen are sufficient for most crops, and direct application of nitrogen may then be restricted to a light stimulating dressing. This is more particularly the case with perennial crops; for annuals intensive green manuring is only exceptionally of service. The green manures also withdraw phosphoric acid and potassium from the deeper layers of soil, and in decaying enrich the surface layers in these substances and also in lime and magnesia. Rain or irrigation water subsequently carry these plant foods down to the root zone. Efficient green manuring may thus be regarded as multiplying the root zone of the crop, since from the chemical point of view the soil is utilised to a great depth. In spite of the general view that humus is of little importance in the tropics the experience of the most progressive tropical countries has been that, just as in temperate climates, second to water, humus is the most important factor in crop production. The conservation and building up of humus is one of the most important points of soil management in the tropics. Thoroughly shading the soil in order to avoid destruction of humus, and sowing all unused land with leguminous vegetation, are operations which work wonders on the soil both physically and chemically, and which very quickly pay for their cost by economising artificial manures.

In regions of heavy rainfall, where areas may be fallow for a number of years. *Mimosa invisa* is

particularly suitable. As references to this subject are scattered through the literature, the following table gives a list of plants which have proved satisfactory as green manures for various purposes:

I. Where land has been cleared of trees and where fields are to be fallowed for a long time—

Mimosa invisa, which is specially useful for heavy soils where the subsoil is impermeable, or a mixture of the following leguminosae.

II. Leguminous trees—

Acacia decurrens, *villosa*, *Albizzia falcata*.
Leucaena glauca.

III. Green manures of bushy growth—

Crotolaria anagyroides, *Usaramoensis*, *juncea*.
Cassia hirsuta, Leschenaultiana, *mimosoides*, *obtusifolia*, *patellaria*, Tora.
Tephrosia candida, *noctiflora*, *purpurea*, *vestita*, *villosa*, Vogelii, Vogelii Hook.

IV. Creepers—

Canavallia ensiformis.
Calopogonium muconoides.
Centrosema pubescens.
Indigofera erecta, *endecaphylla*, *hirsuta*, *suffruticosa*.
Puelaria phaseoloides.
Vigna Hosei, Hosei Back. (*Dolichos* Hosei Craib.)

The two last, *Puelaria* and *Vigna*, will thrive even when heavily shaded.

It is always worth while to make experiments with leguminous plants native to the district in order to see whether they are suitable for cultivation. Valuable new varieties may be found in this way.

Attention may also be drawn to another factor affecting the value of humus in respect to tropical crops. The carbon dioxide which plants need as raw material is derived from the air. In dry regions where natural vegetation is sparse the few observations that have so far been made indicate clearly that the carbon dioxide content of the air near the soil surface has rather low values. Thus the more organic matter in the soil to release carbon dioxide during decomposition the less is the likelihood that lack of carbon dioxide will be a factor limiting the yield. In this sense green manuring not only builds up the humus content of the soil but is also manuring with carbon dioxide.

The importance of humus for biological processes in the soil must be as great as in temperate regions, but since development has been recent there is a lack of extended investigations on this matter.

It has already been noted that full exploitation of the resources of green manuring is chiefly important for the perennial crops of the tropics. For these it is clear that continued withdrawals of plant foods in harvests cannot be wholly compensated by addition of artificial fertilisers owing to limitations imposed by the volume of soil used by the crop. To maintain the nitrogen balance is the least difficult problem, since very considerable amounts of nitrogen can be taken from the air by intensive green manuring. As regards the other plant foods, it is highly desirable to supplement the green manures as far as may be by applications based on the requirements of the soil as determined by chemical analysis. The plant foods held by the green manures are in the course of time made available for the main crop in a specially suitable form.

Apart from other difficulties, the question of the time required before an application of fertiliser takes effect on a perennial crop or on a soil of

high sorbtive capacity makes it very doubtful whether manurial trials on perennial crops are of any value in determining their nutritional requirements. It rarely happens that conclusive results are obtained soon enough to be of use in agricultural practice. Where perennial crops are concerned there is no satisfactory alternative to basing a manurial programme on soil analysis carried out and discussed by specialists. For tropical soils modern methods of investigation are fully capable of providing this information, which eliminates loss of time in misdirected experiments and makes possible the use of fertilizers on a practical scale so as to take immediate advantage of favourable prices in the world market. With annual crops extended use of green manures, with the attendant possibilities of economy, is practicable only while the fields are bare, and even then is of limited value. The yields of annual crops can be maintained at a satisfactory level only by application of artificial manures on a scale broadly similar to that of temperate climates. Replicated manurial experiments are of course of greater value here than in the case of perennial crops, but in order to avoid unnecessary elaboration a preliminary soil analysis should be made. When this is carried out with care it will indicate what substances may prove deficient and will provide information which no field trial can yield, in suggesting a manurial programme based on the particular reaction requirements of the plants and on the sorbtive peculiarities of the soil under cultivation.

APPENDIX I

TABLE FOR DETERMINATION OF THE MOST IMPORTANT SOIL MINERALS

Opaque

Substance	Form of Occurrence	Colour	Special Characteristics
Magnetite		Black	Lustrous, strongly magnetic
Sphene	well-formed crystals	Black	
Pyrite		Yellow	Lustrous
Iron concretions	Grains, scoriaceous concretions	Brown to black	
Lime concretions	Irregular or round grains	Whitish gray sometimes black at the surface	In dry climates often coated with manganese; occasionally show structure
Charcoal	Fragments	Black	

Isotropic [Singly Refractive]					Anisotropic [Doubly Refractive]										
					Straight Extinction					Oblique Extinction					
Mounting material	Substance	Form of Occurrence	Colour	Refractive Index	Substance	Form of Occurrence	Colour	Pleochroism	Refractive Index	Substance	Form of Occurrence	Colour	Pleochroism	Refractive Index	Extinction Angle *
	Opal	Round grains	Colourless to blue iridescent	1·46	Tridymite	Flakes	Colourless to yellowish	—	1·477						
Xylene				1·495	Calcite	Grains and flakes	Colourless to yellowish	—	1·487 to 1·500	(Xylene				1·495)	
	Glass	Grains and splinters, conchoidal fracture	Colourless to brown	1·49–1·63	Dolomite	Grains and flakes	Colourless to yellowish	—	1·50–1·68	Orthoclase	Usually twinned flakes and prisms	Colourless to flesh colour	—	1·516 to 1·525	5–10°
	Leucite	Grains with lattice structure	Colourless to yellowish	1·509	Magnesite	Grains and flakes	Colourless to yellowish	—	1·515	Microcline	Flakes with lattice structure	Colourless	—	1·512 to 1·529	5–17°
Chlorobenzene				1·525	(Chlorobenzene				1·525)	(Chlorobenzene				1·525)	
	Glass	(As above)			Nepheline	Small prisms never occurring with quartz	Colourless to yellowish	—	1·538	Gypsum	Flakes, fibres, grains, often in aggregates	Colourless	—	1·527	Up to 54°
	Chalcedony	Grains and flakes, sometimes radial fibres	Colourless to brown	1·532	Chalcedony	(*See* Isotropic minerals)				Hydrargillite	Flakes and small prisms, often in aggregates	Colourless	—	1·535	Up to 65°
					Calcite	(As above)				Albite	Flakes and small prisms, twin lamellae	Colourless to brown	—	1·535	4–19°
					Dolomite	(As above)									
Eugenol				1·542	(Eugenol				1·542)	(Eugenol				1·542)	
	Glass	(As above)			Quartz	Irregular grains, splinters, pyramids	Colourless to bluish	—	1·545	Kaolin	Clusters of flakes	Colourless-yellowish	—	1·550	20°
					Calcite	(As above)				Oligoclase	Flakes and small prisms, twin lamellae	Colourless-yellowish	—	1·543	0–12°
					Dolomite	(As above)									
Nitrobenzene				1·554	(Nitrobenzene				1·554)	(Nitrobenzene				1·554)	
	Glass	(As above)			Talc	Clusters of flakes	Greenish-bluish	—	1·55–1·59	Andesine	Flakes and small prisms, twin lamellae	Colourless-yellowish	—	1·560	2–19°
	Colloidal iron phosphate	Small irregular grains	Blue to green	1·580	Muscovite	Clusters of flakes	Colourless to gray	—	1·56–1·60	Labradorite	(Ditto)	Colourless-yellowish	—	1·563	5–28°
Cinnamon oil				1·605	(Cinnamon oil				1·605)	Bytownite-anorthite	(Ditto)	Colourless-yellowish	—	1·588	9–50°
	Glass	(As above)			Biotite	Usually weathered	Brown-black	—	1·62	Green hornblende	Small prisms and plates	Blue-green to brown	Green to brown	1·63–1·65	12–20°
	Iron silicate	Small irregular grains and agglomerates	Yellow to green	1·60	Apatite	Grains and small prisms	Colourless to brown	?	1·635						
α-Monochlornaphthalene				1·650	(α-Monochlornaphthalene				1·650)	(α-Monochlornaphthalene				1·650)	
					Enstatite	Grains and small prisms	Brown-green	—	1·660	Augite	Small prisms and flakes	Black to violet	?	1·710	43–54°
Potassium mercuric iodide				1·720	(Potassium mercuric iodide				1·720)	(Potassium mercuric iodide				1·720)	
					Hypersthene	Small prisms	Brown-black	Green-brown	1·730	Brown horn-	Small prisms and flakes	Black to brown	Green to brown	1·750	0–10°

APPENDIX II

THE PRINCIPAL IGNEOUS ROCKS

(Based on Heide, Weinschenk, Milch)

Plutonic	Hypabyssal	Volcanic	Principal Constituent Minerals	Accessory Minerals	Na_2O	K_2O	MgO	CaO	P_2O_5	Habit	Weathering
Granite . .	Quartz porphyry, pitchstone	Rhyolite (= ger. Liparite)	Potash felspars, plagioclase, quartz (glass)	Micas, hornblende, augite, iron ores, apatite	2·8–3·5	3·9–4·8	0·4–0·5	1·1–0·5	0·01–0·15	Granite, light coloured; volcanic, darker coloured	Relatively rapid weathering, granite weathers more easily than rhyolite
Soda granite .	..	Pantellurite, keratophyre	Albite, augite, quartz	..	7·0–8·0	0·2–4·0	..	..	..	..	..
Syenite . .	Syenite porphyry	Trachyte	Alkali felspars, biotite, hornblende	Magnetite, garnet	3·8–4·1	4·5–5·1	1·9–2·7	3·4–4·3	0·1–0·24	Flesh coloured to gray	Rather more freely than granites
Nepheline syenite	..	Phonolite, leucitophyre	Alkali felspar, nepheline leucite, pyroxene	Iron ores, apatite	8·8–9·0	4·5–5·2	0·3–0·6	1·5–1·7	0·12–0·24	Greenish to brown, greasy looking	Slow, but produce good soils
Quartz diorite .	Quartz porphyrite	Dacite	Plagioclase, quartz, hornblende	Biotite, augite	3·6–4·2	2·5–3·2	1·5–2·0	3·0–4·0	0·1–0·2	Light coloured	Slow weathering
Diorite . .	Porphyrite	Andesite	Plagioclase, hornblende	Augite, apatite, iron ores	3·6–4·2	2·0–2·4	1·2–4·4	3·3–7·3	0·08–0·32	Gray to black	Rather more easily weathered, usually yields red earths
Gabbro norite	Dolerite	Basalt	Plagioclase, augite	Olivine, iron ore, apatite	2·2–3·2	0·8–1·8	5·9–8·9	8·1–11·5	0·2–0·5	Gray-green to black	Slow weathering, producing very dark, often rich red earths
Missourite, potash gabbro	..	Olivine leucitite	Leucite, augite, olivine	Iron ores, apatite, hornblende	1·1–1·5	4·4–7·7	3·4–13·0	7·0–11·5	0·2–0·8	Gray to greenish black	As gabbro
Kentallenite, basic potash gabbro	..	Trachybasalt	Orthoclase, biotite, plagioclase, olivine	Iron ores, apatite	3·1	2·6	15·2	7·9	?	Dark brown	As gabbro
Soda gabbros, including essexite, theralite, ijolite	Analcite dolerite	Nepheline tephrite, analcime basanite	Plagioclase, nepheline, olivine	Orthoclase, iron ores, apatite	5·5–5·9	2·7–3·1	2·3–3·5	5·6–7·5	0·5–0·8	Gray-green to black	As gabbro
..	..	Melilite basalt	Melilite, olivine, augite	Iron ores, apatite	3·5–4·0	0·8–2·6	3·6–10·5	2·5–18·3	0·08–1·2	Light to dark gray	Weathers easily and often forms iron crusts
Anorthosite .	..	..	Labradorite or anorthite	Augite, biotite	4·05–5·0	0·6–0·78	1·0–3·6	8·7–15·7	trace	White or light coloured	Easily weathers to light-coloured soils
Peridotite . .	..	..	Olivine	Augite, hornblende, biotite, iron ores	0·4–0·6	0·2–0·8	19·5–29·2	6·3–13·0	0·05–0·14	Gray-green to black	Weathering fairly easily to very dark soils
Pyroxenite .	..	..	Augite	Hypersthene							

APPENDIX III

The following references may prove of value to the English-speaking reader. The list was prepared at the Imperial Bureau of Soil Science by courtesy of Sir John Russell, F.R.S., to whom acknowledgement is here made for his help in this and other directions.

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